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Computer simulation, visualization, and synthesis of a digital antenna array used for transmitting and receiving signals in industrial applications

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Research Paper

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Abstract

The article is devoted to computer modeling, visualization, and synthesis of a digital antenna array used for transmitting and receiving signals in industrial applications. The paper proposes an iterative method for the amplitude-phase synthesis of an antenna array according to the requirements for the envelope of the side lobes. The proposed method allows to determine the complex amplitudes of the elements of a digital antenna array for any given weight function, based on the theorems of matrix theory. The difference of the method lies in the iterative procedure for choosing the weight function, taking into account the excess level of the side lobes of the digital antenna array. In this regard, in the course of solving the synthesis problem, a weight function was found that leads to the fulfilment of the requirements for radiation patterns and does not lead to a decrease in the directivity coefficient. The signal-to-noise ratio was used as a criterion. For the first time, an analytical expression is given for the formation of a weight function in the course of an iterative process that takes into account the requirements for the envelope of the side lobes. The operability and convergence of the proposed method was confirmed in the course of numerical studies on the example of a digital antenna array. The performed numerical analysis confirmed the effectiveness of the proposed synthesis method.

Introduction

Antenna arrays are one of the most promising types of antennas, which are increasingly used in various radio electronic systems. Antenna arrays have come a long scientific and practical path of development. The first phased antenna arrays were created more than 35 years ago and since then have been widely used in various radio electronic systems. Interest in them continues unabated today. This is evidenced by the ongoing search for new, effective solutions based on the most modern technologies and capable of significantly expanding the scope of phased array antennas. The development of the theory and technology of phased antenna arrays is currently going in the following most important areas:

(1) the use of active antenna arrays with a large number of new types of elements in advanced radio engineering devices;
(2) development and implementation of new methods for constructing antenna arrays with large openings;
(3) development and improvement of radio engineering elements and methods to reduce interference between elements of antenna arrays;
(4) further development of methods for the synthesis of antenna arrays and automation of their design;
(5) further development and implementation of methods for processing the information received by the antenna array elements, providing, for example, control of the shape of the radiation patterns and automatic phasing of the antenna array elements;
(6) development of methods for controlling the independent movement of individual beams in multibeam phased antenna arrays.

When designing, computer modeling, visualization, and synthesis of antenna arrays, requirements inevitably arise for the level of side lobes of the generated radiation pattern or the envelope of the side lobes [1–5]. Approximate synthesis methods can be used to generate a given side lobe envelope. In this case, the quality of the approximation can be controlled by increasing the values of the weighting function in the required range of angles [6–11]. However, approximation methods often lead to solutions that are inefficient in terms of antenna energy. In this regard, of interest are methods that allow optimizing the antenna energy under restrictions on the envelope of the side lobes. Therefore, creating a method of computer simulation, visualization, and synthesis of a digital antenna array for the industry is an urgent task.

The novelty of the proposed method of amplitude-phase synthesis of the antenna array under given restrictions on the side lobe envelope, based on the use of the matrix synthesis apparatus, lies in the fact that during the iterative procedure for selecting the weight function, it is possible to take into account the excess of the side lobe envelope over the given level of the side lobe of the digital antenna array. Another novelty of the proposed method of amplitude-phase synthesis of the antenna array is to ensure the optimal energy of the antenna under given restrictions on the envelope of the side lobes.

The proposed method for synthesizing an antenna array differs from other methods indicated in papers [1–11] in that this method of amplitude-phase synthesis of an antenna array provides the optimal energy of the antenna under given restrictions on the envelope of the side lobes.

Mathematical model of the antenna array

Let's consider an M-element array, which during the time T receives a signal with a complex envelope $u_0(t)$ from the direction (θ_0, ϕ_0).

Let the radiation patterns of the elements in the composition of the antenna array be described by complex functions $f_m(\theta, \phi)(m = 1, 3, \ldots, M)$, then the radiation patterns of the antenna array can be represented as:

$$F(\theta, \phi) = \sum_{m=1}^{M} A_m f_m(\theta, \phi), \tag{1}$$

where A_m is the complex excitation amplitude of the m-th element.

Obviously, the power of the received signal, taking into account expression (1), is determined by an expression of the form:

$$\begin{aligned} P_0 &= |F(\theta_0, \phi_0)|^2 \int_0^T |u_0(t)| dt \\ &= p_0 \sum_{m=1}^{M} \sum_{n=1}^{M} A_m A_n f_m(\theta_0, \phi_0) f_n^*(\theta_0, \phi_0) = p_0 A S_0 A^H, \end{aligned} \tag{2}$$

where the symbol "*" denotes the operation of complex conjugation; H denotes the Hermitian conjugation of a vector; $p_0 = \int_0^T |u_0(t)| dt$—signal power at the input of the antenna array.

Each channel of the antenna array contains noise with a complex envelope of $n_m(t)$. The total noise power can be represented using the relation

$$\begin{aligned} N &= \sum_{m=1}^{M} A_m \sum_{n=1}^{M} A_n^* \int_0^T n_m(t) n_n^*(t) dt = \sum_{m=1}^{M} A_m \sum_{n=1}^{M} A_n^* I_{m,n} \\ &= A I A^H. \end{aligned} \tag{3}$$

The thermal noise in the channels of the antenna array can be considered statistically independent, with zero mean and equal noise variances σ^2 in each channel. In this case, the off-diagonal elements of the matrix $\boldsymbol{I}$ vanish, and the general expression for the elements of the matrix $\boldsymbol{I}$ can be represented as:

$$I_{m,n} = \begin{cases} \sigma^2, & m = n \\ 0, & m \neq n. \end{cases} \tag{4}$$

The distribution of the power of external interference and noise will be set using function $\rho(\theta, \phi)$. In this case, the resulting noise power at the output of the antenna array can be represented as:

$$\begin{aligned} P &= \sum_{m=1}^{M} \sum_{n=1}^{M} A_m A_n^* \iint_\Omega \rho(\theta, \phi) f_m(\theta, \phi) f_n^*(\theta, \phi) \sin\theta d\theta d\phi \\ &= A S A^H. \end{aligned} \tag{5}$$

Taking into account the introduced notation, the signal/(interference + noise) ratio at the output of the antenna array can be represented in matrix form:

$$q^2 = \frac{P_0}{P + N} = p_0 \frac{A S_0 A^H}{A(S + I)A^H}. \tag{6}$$

Note that in expression (6) the elements of the matrix $\boldsymbol{S_0}$ depend on the direction of maximum radiation patterns. The elements of the matrix $\boldsymbol{S}$ for a given geometry of the antenna array are determined by the spatial distribution of interference and their power. These parameters depend on the form of the function $\rho(\theta, \phi)$. Depending on the emerging interference situation, the matrix $\boldsymbol{S}$ is not always positively definite. On the contrary, matrix $\boldsymbol{I}$ is diagonal, which can always be assigned an inverse matrix. If the noise power is commensurate with the interference power, then the sum $\boldsymbol{S} + \boldsymbol{I}$ is a positive-definite Hermitian matrix.

In matrix theory, there are theorems defining the condition maximum ratio of Hermitian forms [12–15]. Based on these theorems, for a positive-definite Hermitian matrix $\boldsymbol{S} + \boldsymbol{I}$, the maximum expression (8) is achieved for the vector

$$A_{opt} = A_0(A + I)^{-1}, \tag{7}$$

where, as applied to the methods of matrix synthesis of the antenna array, the elements of the vector $\boldsymbol{A_0}$ are described by the expression:

$$\begin{aligned} A_{0m} = exp(-ik(&x_m \sin\theta_0 \cos\phi_0 + y_m \sin\theta_0 \sin\phi_0 \\ &+ z_m \cos\theta_0)), \end{aligned} \tag{8}$$

where (x_m, y_m, z_m) – are coordinates of phase centers of antenna array elements; k is the wave number.

Substantiation of the synthesis method

Let us consider the application of the matrix model of the antenna array to solve the problem of forming the required envelope of the side lobes.

Let $r(\theta, \phi)$ be a real function describing a given side lobe envelope, which is given in the Ω_{SL} region. It is required to find a vector A_{opt} that provides the maximum functional

$$q^2(A) = \frac{A S_0 A^H}{A(S + I)A^H} \tag{9}$$

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and allows one to form a normalized radiation pattern of the antenna array, which in the Ω_{SL} region satisfies the condition

$$|F(\theta, \phi)| \leq r(\theta, \phi). \tag{10}$$

Comparison of functional (9) with expression (6) shows that they coincide up to a constant factor equal to p_0. In this regard, to solve the formulated synthesis problem, it is possible to use expression (7).

Based on expression (7), it can be argued that in the absence of interference, when all elements of the matrix $\boldsymbol{S}$ are equal to zero, the maximum of expression (9) is achieved at $\boldsymbol{A}_{opt} = \boldsymbol{A}_0$. This solution also corresponds to the maximum value of the directivity of the antenna array. From the theory of matrix synthesis, it is also known that in the presence of one or more interferences, as a result of applying expression (7), the maximum value of the signal/(interference + noise) ratio is achieved due to the simultaneous formation of "nulls" of the radiation patterns in the directions of interference and maximizing the power P_0 toward the signal source. In this case, the depth of the formed zeros depends on the specified interference power. Expression (7) is also used to form extended nulls of the radiation patterns. In this case, the depth of interference suppression also depends on the distribution of interference power within the area Ω_{SL}. This means that the choice of function $\rho(\theta, \phi)$ affects the nature of the distribution and the envelope of the side lobes of the generated radiation patterns $|F(\theta, \phi)|$. At the same time, the relationship between function $\rho(\theta, \phi)$ and the envelope of the side lobe is not unambiguous. For example, if the direction of arrival of the interference coincides with the zero of the radiation patterns, then this interference will not affect the amplitude-phase distribution. Therefore, to solve the formulated problem, it is necessary to find a weight function $\rho(\theta, \phi)$ that, after substitution into expression (5) and determination of the amplitude-phase distribution by formula (7), will provide the maximum value of the expression (6) and fulfillment of requirement (9).

Let us represent the solution of the formulated synthesis problem in the form of an iterative process, at each step of which, with the number t, the form of the distribution function of external noise sources $\rho^t(\theta, \phi)$ is specified. Here and below, the value in triangular brackets will denote the step number of the iterative process.

When initializing the iterative process, we set $\rho^{t=0}(\theta, \phi)$. In accordance with expression (7), with such an initialization of the iterative process, we obtain $A^0_{opt} = (1/\sigma^2)A_0$, from which, using formula (1), we can calculate the radiation patterns of the antenna array $F^0(\theta, \phi)$.

Taking into account the introduced notation, at an arbitrary step $t \geq 0$ of the iterative process, we will define a new weight function

$$\rho^t(\theta, \phi) = \begin{cases} 0, \ (\theta, \phi) \notin \Omega_{SL}; \\ \rho^{t-1}(\theta, \phi) + \alpha, \ |F^{t-1}(\theta, \phi)| \geq r(\theta, \phi); \\ \rho^{t-1}(\theta, \phi)/2, \ |F^{t-1}(\theta, \phi)| \leq 0, 7r(\theta, \phi); \\ \rho^{t-1}(\theta, \phi), \ 0, 7(\theta, \phi) \leq |F^{t-1}(\theta, \phi)| \leq r(\theta, \phi). \end{cases} \tag{11}$$

Consider expression (10) in more detail. Condition $\rho^t(\theta, \phi)$ at $(\theta, \phi) \notin \Omega_{SL}$ determines that there are no external interference sources in the main beam region. This is part of the expression (11) not dependent on iteration number t.

If in some direction $(\theta, \phi) \notin \Omega_{SL}$ at the previous step the value of the amplitude pattern $|F^{t-1}(\theta, \phi)|$ exceeded the specified level of the side lobe envelope, then this means that the weight function $\rho^t(\theta, \phi)$ needs to be increased. In this regard, this situation corresponds to the second line of the expression (10) and

$$\rho^t(\theta, \phi) = \rho^{t-1}(\theta, \phi) + \alpha, \tag{12}$$

where the coefficient $\alpha \geq 0$ determines the rate of change of the function $\rho^t(\theta, \phi)$.

The reverse situation is also possible, in which the level of the side lobes in the direction (θ, ϕ) is noticeably lower than the given envelope of the side lobes. If in this direction the grating factor ensures the formation of zero radiation patterns, then the value of the function $\rho^t(\theta, \phi)$ will not affect the solution of the synthesis problem according to formula (7). However, much more often the situation arises in which the requirements for the envelope of the side lobe are met at the expense of the loss of antenna gain when the level of side lobes is reduced in the entire region $(\theta, \phi) \in \Omega_{SL}$. In this case, it is necessary to decrease the values of function $\rho^t(\theta, \phi)$. This is achieved using the third line of expression (11). It should be noted that the numerical coefficient of 0.7 in the third and fourth lines of expression (11) determines the accuracy of the approximation given by the side lobe envelope. In fact, with its help, a little lower than the specified side lobe envelope, another auxiliary side lobe envelope is formed, with the help of which the sensitivity of the selected weight function to the level of the side lobes of the generated radiation patterns is regulated. The fourth line in the formation of the function $\rho^t(\theta, \phi)$ corresponds to the case in which the level of side lobes, on the one hand, does not exceed the specified level and is in close proximity to the required level. In this case, as can be seen from expression (10),

$$\rho^t(\theta, \phi) = \rho^{t-1}(\theta, \phi). \tag{13}$$

After the formation of the function $\rho^t(\theta, \phi)$ formula (5), the elements of the matrix $\boldsymbol{S^t}$ can be determined, and then, by formula (7), the amplitude-phase distribution A^t_{opt} can be determined.

Exit rules from the iterative process can be set when one or more conditions are met:

(1) reaching the limited number of iterations;
(2) meeting the requirements for the level of side lobes;
(3) achievement of the minimum allowable value of the directivity of the antenna array.

Cyclic repetition of the process of refining function $\rho^t(\theta, \phi)$ by formula (10) is equivalent to the selection of such a spatial distribution of sources of external interference, in which, according to formula (7), the maximum value of the expression (6), which determines the value of the signal/(interference + noise) ratio, is provided, and the requirements for the level of side lobe are met. As a result, the main result of the proposed method is achieved: the formation of directivity diagrams with the best energy when meeting the requirements for the level of side lobe.

Results of numerical studies

As the first example confirming the operability of the method, the problem of synthesizing an $M = 32$ elements linear equidistant antenna array with a spacing between radiators $d = 0, 55\ \lambda$ and directivity diagrams of elements described by complex functions

$$f_m(\theta) = exp(ikx_m \sin\theta)\cos\theta, \tag{14}$$

where k is the wave number; $x_m = d(m - 0.5(M+1))$ is the coordinate of the phase the center of the m-th element of the antenna array.

The given side lobe envelope was determined by the formula

$$r(\theta) = \begin{cases} 0, (\theta) \in (-55^\circ, -45^\circ); \\ 0, 02\cos(\theta),\ \theta \in [-90^\circ, -55^\circ] \cup [-45^\circ, 8, 2^\circ] \cup [31, 8^\circ, 90^\circ]; \\ 0, 07\cos(\theta),\ \theta \in (8, 3^\circ, 14, 1^\circ) \cup (25, 9^\circ, 31, 7^\circ). \end{cases} \tag{15}$$

In this case, the maximum radiation pattern was oriented in the direction $\theta_0 = 20^\circ$. It should be noted that the realized radiation pattern describes a continuous field distribution. In this regard, if the given envelope of the side lobe contains zero sections, then in this case there can only be an approximate solution to the synthesis problem. In this case, as a result of the synthesis, such a single solution will be selected that corresponds to the minimum level of side lobes in the zero section of the side lobe envelope when implementing the requirements for the side lobe envelope in the remaining sections and the maximum value of the antenna array directivity. If there are no zero sections of the side lobe envelope, then in the process of solving the synthesis problem, a solution will be found that satisfies the requirements for the side lobe envelope and maximizes the directivity of the antenna array.

In Fig. 1, the black dashed curve characterizes the requirements for the envelope of the side lobe, and the blue curve illustrates the shape of the antenna array radiation patterns when using the amplitude distribution falling according to the "cosines" law in the aperture.

As can be seen, the use of a standard distribution in the aperture makes it possible to obtain a radiation pattern whose side lobe envelope practically corresponds to the specified one. This radiation pattern corresponds to a "flat" directional coefficient calculated by the formula [16–18]

$$D = \frac{\pi |F(\theta_0)|}{\int_{-\pi/2}^{\pi/2} |F(\theta)|^2 d\theta} \tag{16}$$

and equal to 16.1 dB. In accordance with [19–24], the directivity of a flat antenna array is the product of the flat directivity for orthogonal sections of the radiation patterns, divided by the number μ.

The solid red curve in Fig. 1 corresponds to synthesized radiation patterns, which was obtained using the proposed method after performing 500 iterations $\alpha = 0.001$. The estimate of the directivity, in this case, is 16.7 dB.

In order to form the realizable requirements for the side lobe envelope in the first line of expression (14), the zero level was changed to a level of 0.005 (−46 dB). These initial data in Fig. 1 correspond to the green curve. The general approach to solving the synthesis problem with a change in expression (15) remained the same [25–32].

From a comparison of the curves in Fig. 1, it follows that the proposed method ensured the formation of a narrower beam and a qualitative approximation of the envelope of the side lobe to the specified one in the entire region Ω_{SL}.

As a second example, the problem of synthesizing an antenna array consisting of 32×32 elements located at the nodes of a rectangular grid with a step 0.55 λ along at each coordinate was solved. The side lobe envelope was set to two levels, 0.07 and 0.02. In

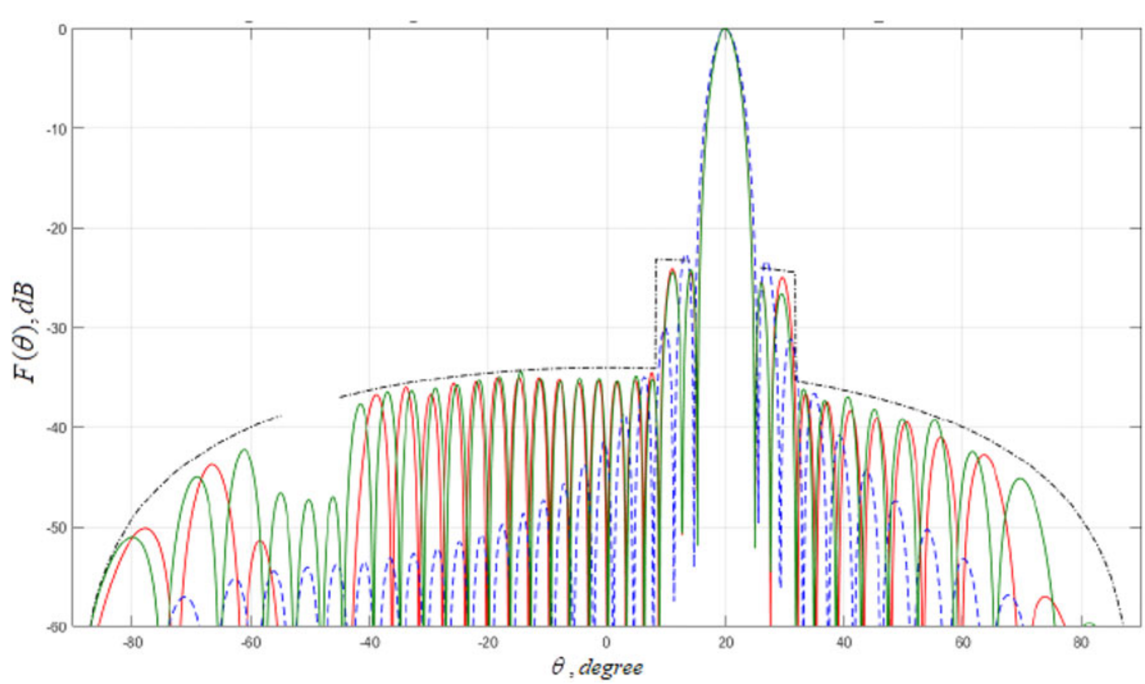

Fig. 1. Given side lobe envelope (dashed-dotted curve) and directivity patterns of a linear antenna array obtained using the amplitude distribution falling according to the "cosine" law and the distribution (blue curve) obtained by the proposed method with a zero region of the side lobe envelope (red curve) in the absence of a zero region, the envelope of the side lobe (green curve).

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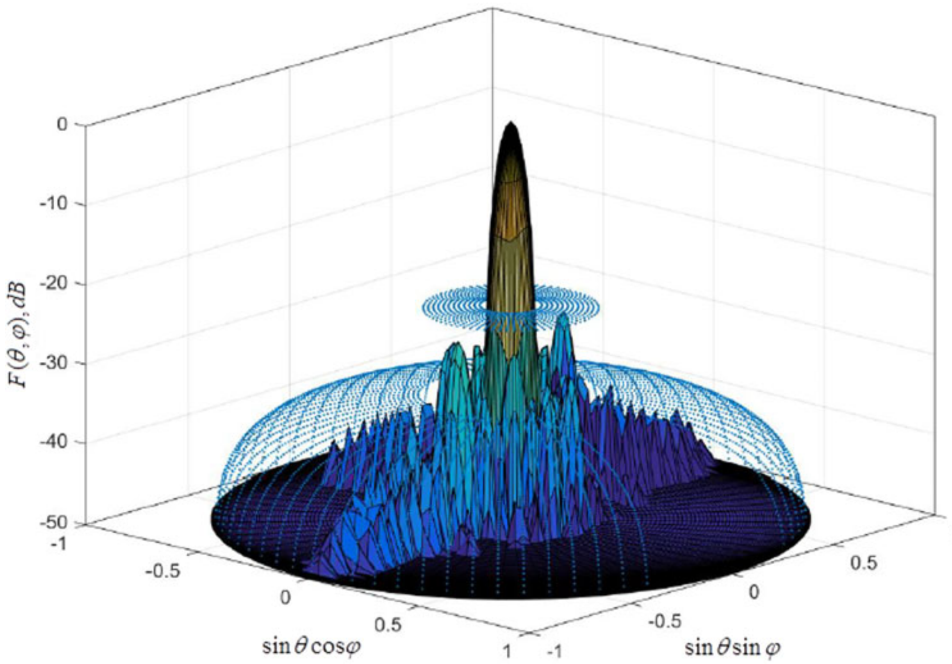

Fig. 2. Volumetric radiation pattern of a 32 × 32 element antenna array and a given envelope of the side lobes.

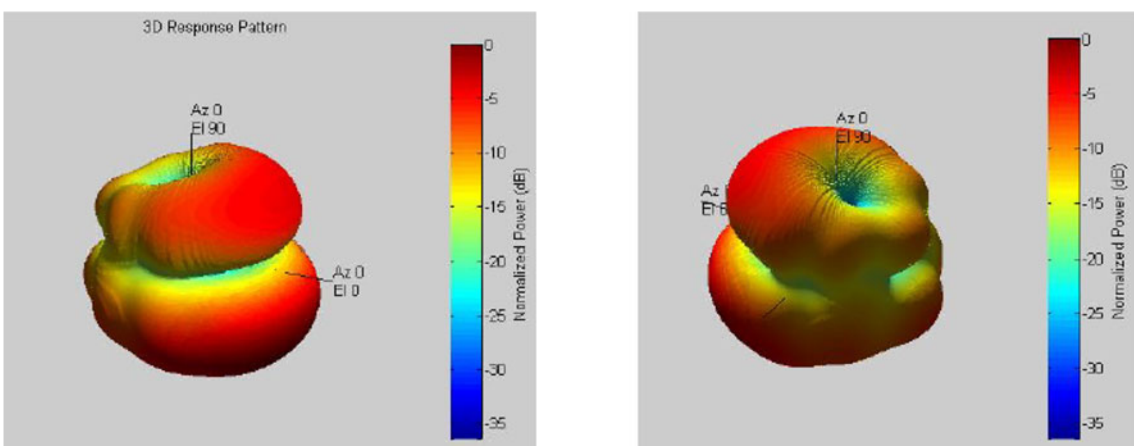

Fig. 3. Angle of rotation −30°.

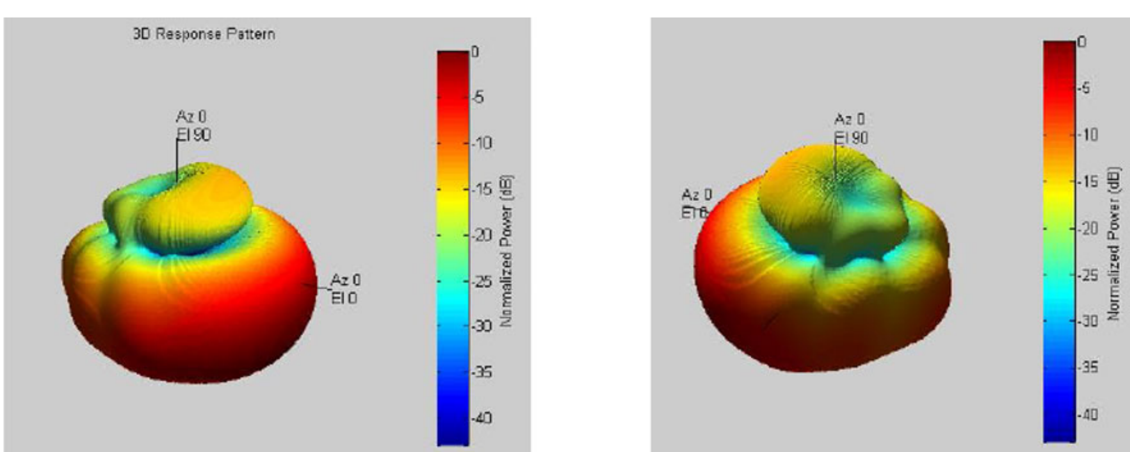

Fig. 4. Angle of rotation −20°.

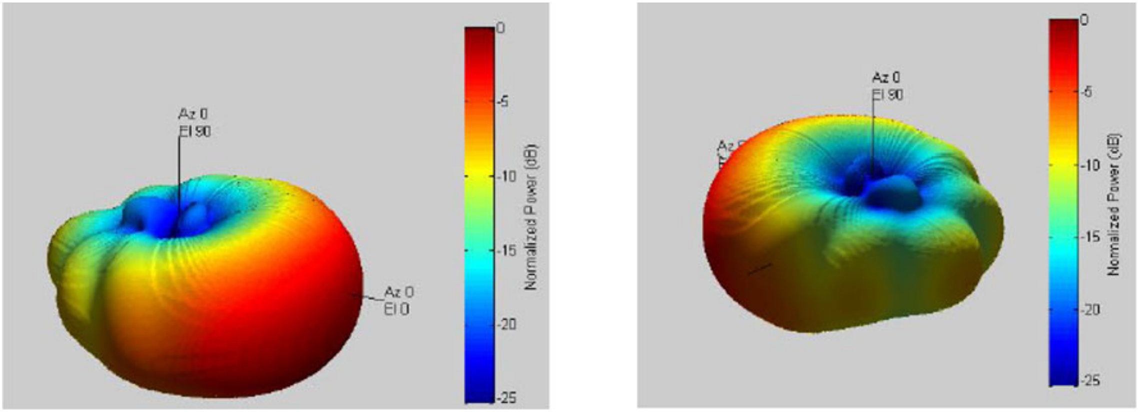

Fig. 5. Angle of rotation −10°.

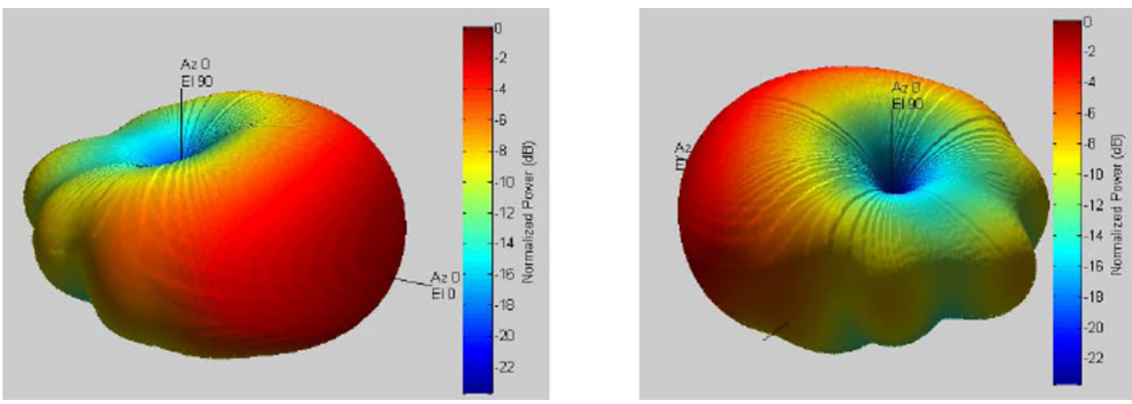

Fig. 6. Angle of rotation 10°.

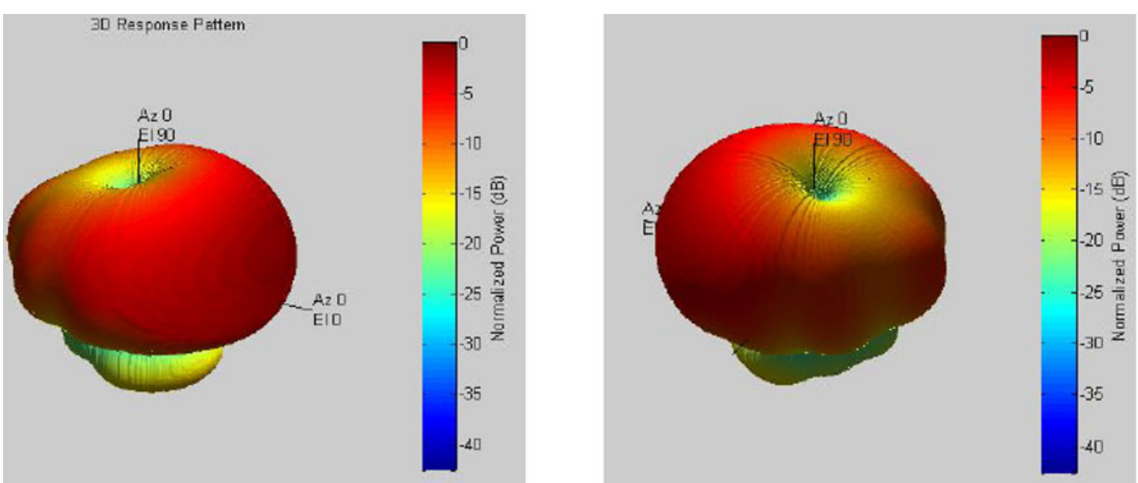

Fig. 7. Angle of rotation 20°.

addition, in the sector of angles $\phi \in [-15°; 15°]$ $\sin\theta \geq 0.3$ it was required to ensure a low level of side lobes. In this case, the directivity diagrams of the elements were described by complex functions

$$f_{mx+M_x(my-1)}(\theta,\phi) = exp(ik\sin\theta(x_{mx}\cos\phi + y_{my}\sin\phi))\cos\theta, \qquad (17)$$

where m_x, $m_y = 1, 2, \ldots, 32$ are the numbers of elements in the column and row of the antenna array, respectively; (x_{mx}, y_{my}) −are coordinates of the phase center of the element of the antenna array placed in the column with the number m_x and the line m_y.

Figure 2 shows the volumetric radiation pattern obtained as a result of solving the synthesis problem after 200 iterations $\alpha = 0.01$.

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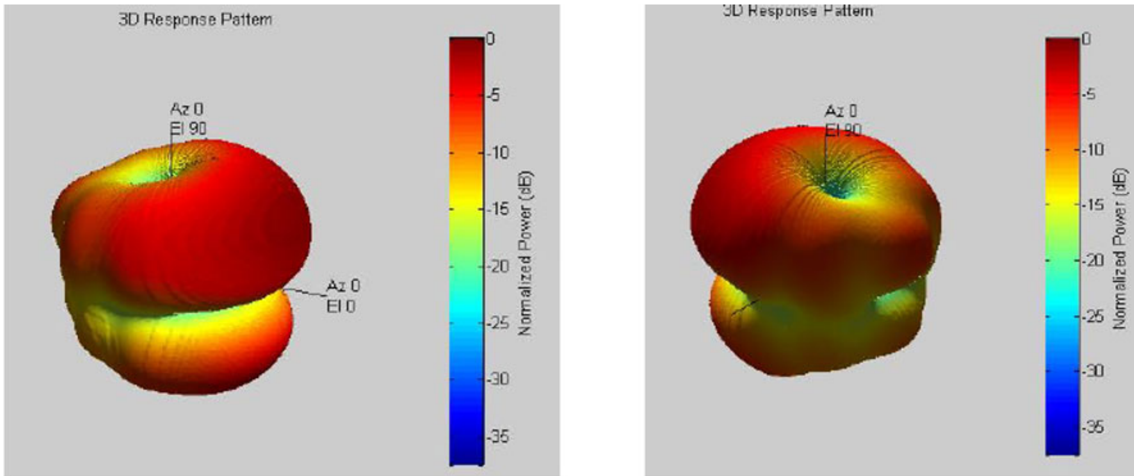

Fig. 8. Angle of rotation 30°.

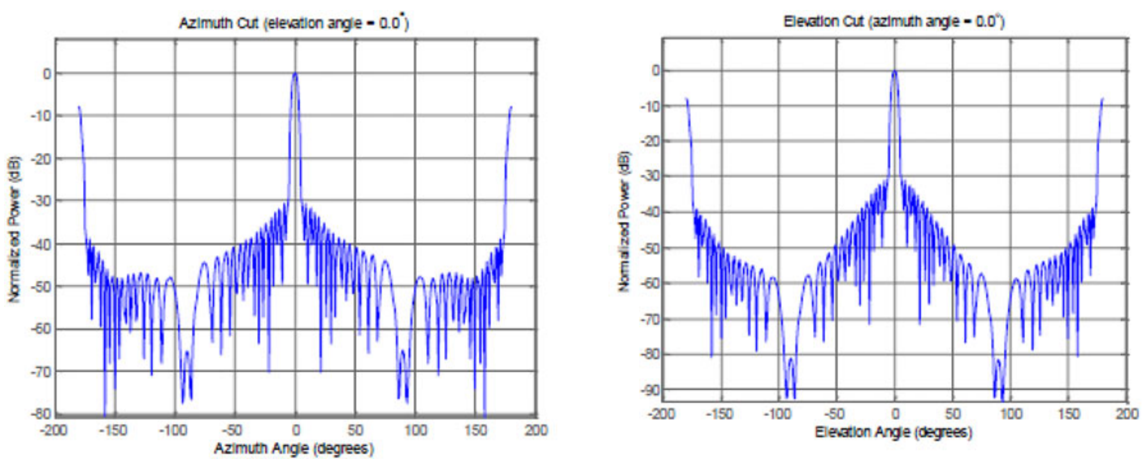

Fig. 9. Azimuth 0°, elevation 0°.

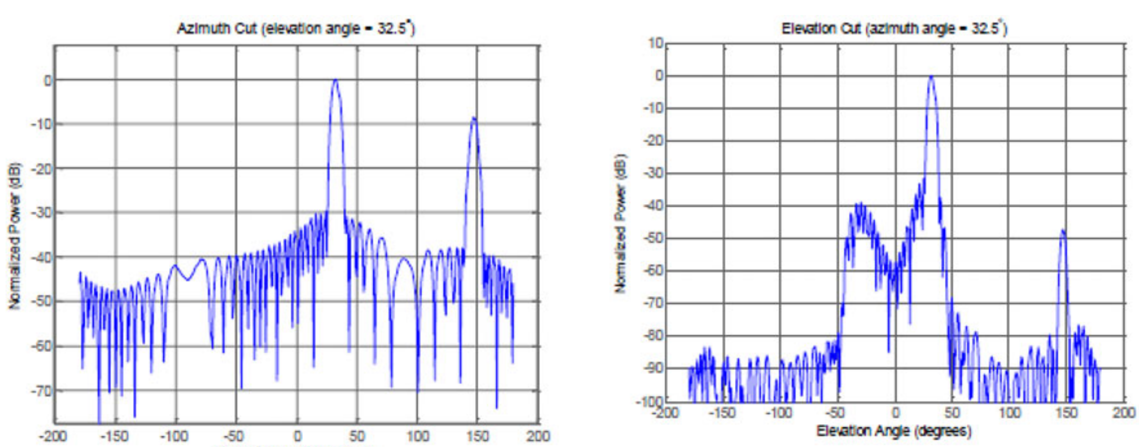

Fig. 10. Azimuth 32.5°, elevation 32.5°.

The same figure shows the selected envelope of the side lobes. It can be seen that the synthesis goal has been achieved and all side lobes have a level below the specified one. The maximum directivity of the considered antenna array with uniform in-phase excitation was equal to 35.9 dB. During the iterative process, a monotonous decrease in the directional coefficient and an excess of the level of side lobes over a given envelope of side lobes was observed. So, by the 200th iteration, the value of the directivity

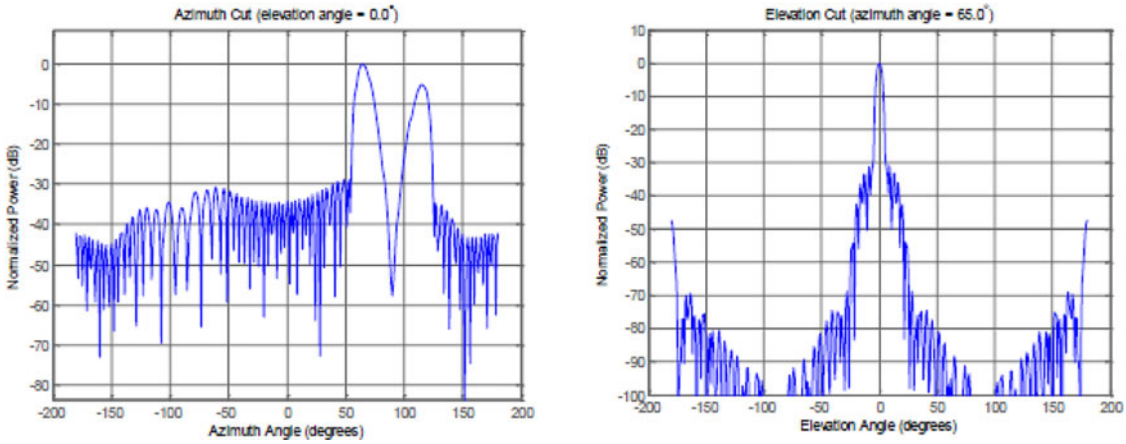

Fig. 11. Azimuth 65°, elevation 0°.

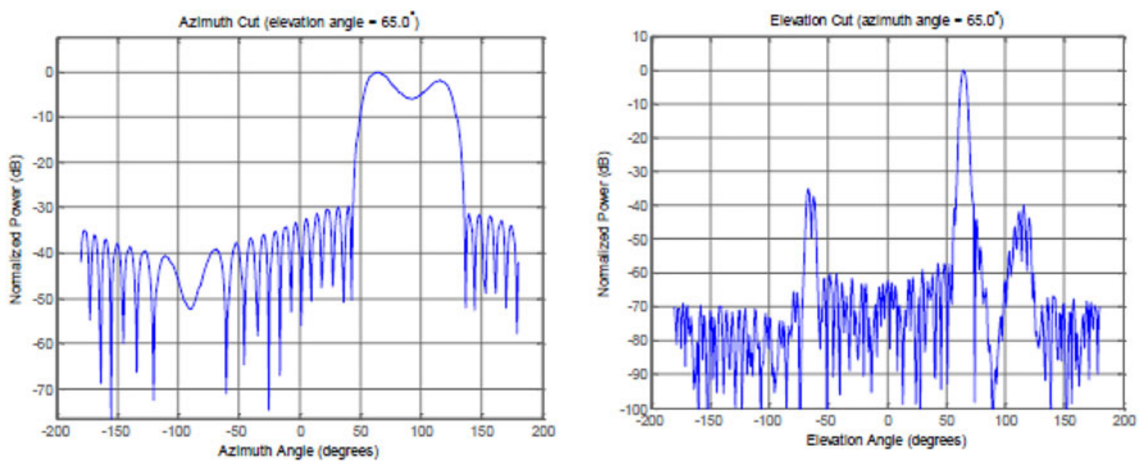

Fig. 12. Azimuth 65°, elevation 65°.

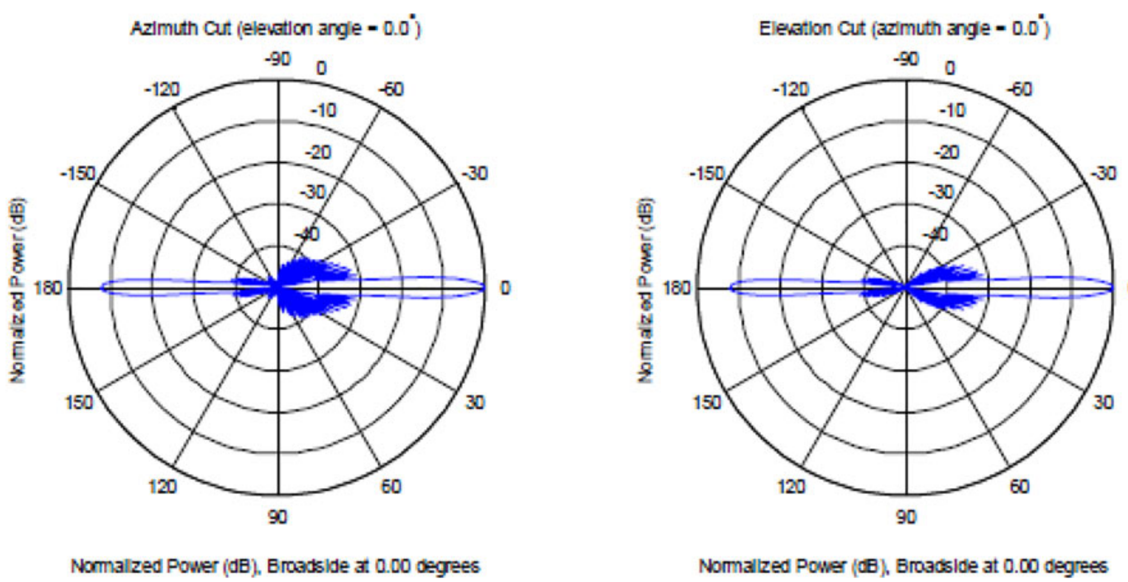

Fig. 13. Azimuth 0°, elevation 0°.

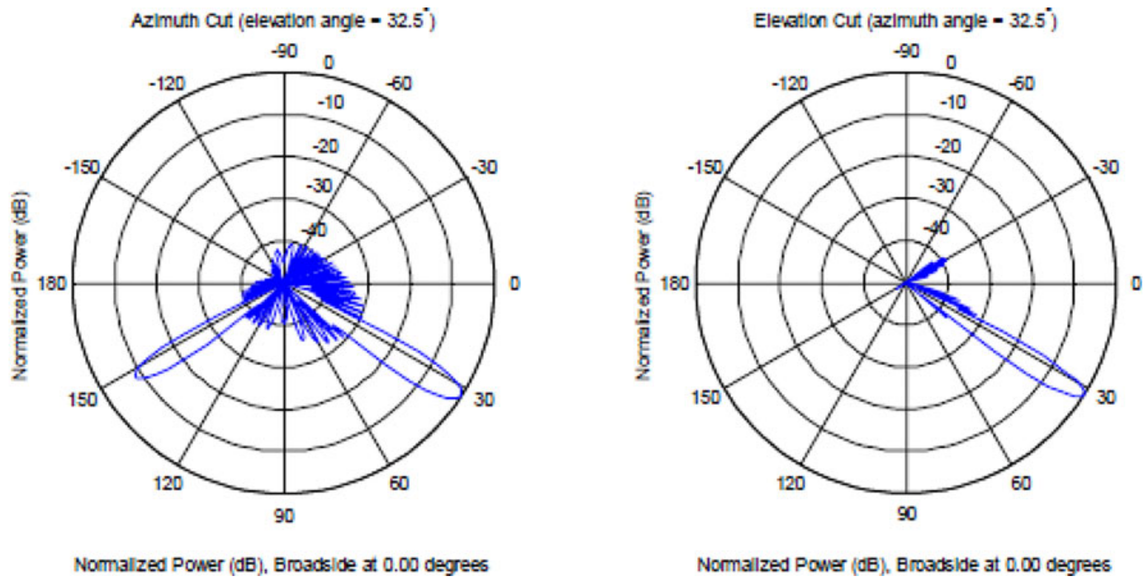

Fig. 14. Azimuth 32.5°, elevation 32.5°.

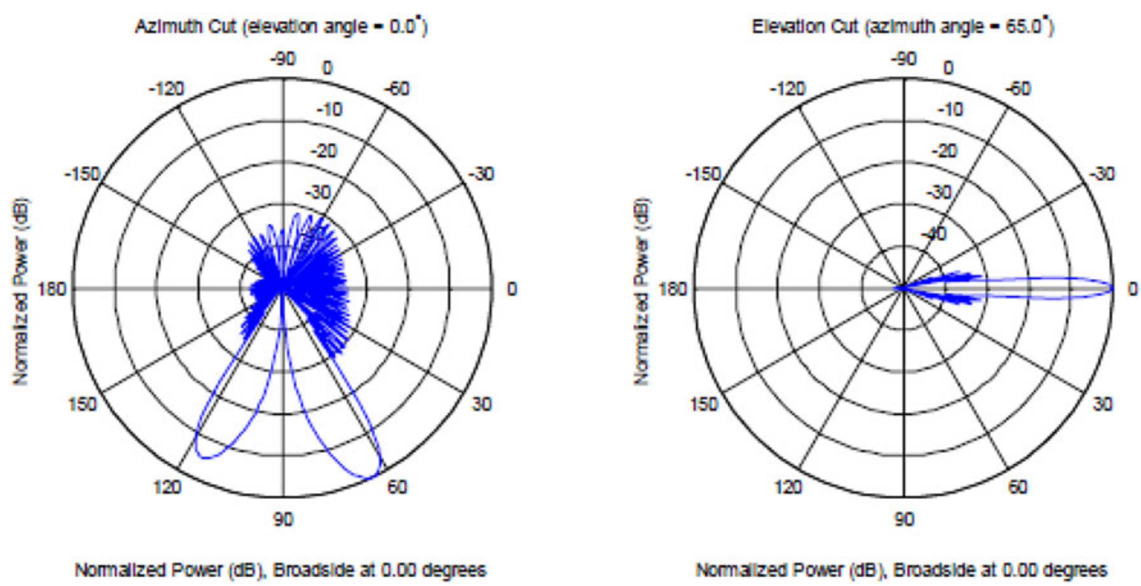

Fig. 15. Azimuth 65°, elevation 0°.

coefficient decreased to 33.54 dB. A further decrease in the directivity is likely to be associated with the limits of the areas of the main beam and side lobes.

The radiation patterns of a single waveguide emitter in the polar coordinate system are shown in Figs 3–20.

The results obtained demonstrate the applicability of the proposed method to solve the problems of synthesis of both linear and planar antenna arrays. In the case of synthesizing a flat antenna, the time for solving the problem increases significantly, which is associated with the need to invert the matrix $\boldsymbol{S}+\boldsymbol{I}$. A reduction in computational costs can be achieved when forming an undeflected radiation pattern with a symmetric side lobe envelope by using either half or even a quarter of the antenna aperture in the synthesis. In addition, based on the proposed method, it is possible to propose algorithms in which the weight function is formed faster, where the excess of the side lobe level over the side lobe envelope is higher and slower otherwise.

Discussion

The proposed technique makes it possible to find the required amplitude-phase distribution in a relatively short time (seconds). The algorithm constructed to obtain the results is not optimal in terms of speed and can be improved. Increasing the speed of calculations is possible with the use of specialized hardware. When solving the adaptation problem, criteria are established that are related to the signal, and not to the radiation patterns of the antenna array; for example, the minimum error when compared with the reference signal. As a result, the optimal vector of weight coefficients is found, including using evolutionary optimization

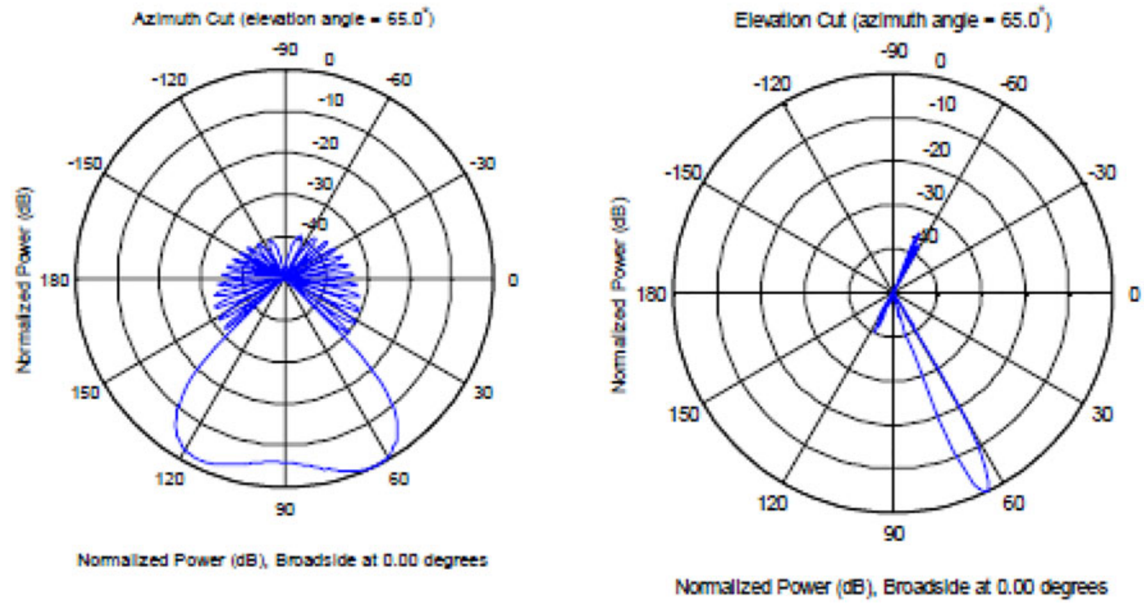

Fig. 16. Azimuth 65°, elevation 65°.

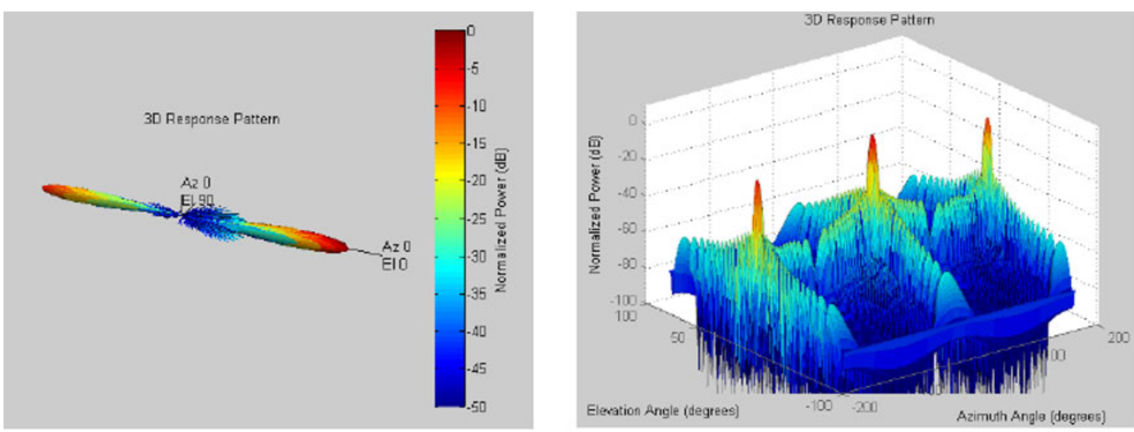

Fig. 17. Azimuth 0°, elevation 0°.

algorithms. This vector corresponds to a radiation pattern of a certain shape. With the help of the proposed technique, it is possible to evaluate the potential capabilities of the antenna during adaptation, taking into account mutual connections; for example, the simulation method. The technique assumes a fixed position of the radiating elements, but it can be applied to the design of reconfigurable antenna arrays.

The work of [33] considers the issues of a printed reconfigurable asymmetric antenna based on new metamaterial structures for 5 G applications, [34] proposes a scheme of a metamaterial patch antenna with circular polarization for modern applications, and analysis of an innovative fractal asymmetric antenna is carried out in [35]. For MIMO state-of-the-art 5 G applications, [36] considers the optical remote control of a miniaturized self-powered 3D reconfigurable MIMO antenna array printed on CRLH for 5 G applications, [37] simulates a miniature reconfigurable MIMO antenna array with optical remote control, printed on a CRLH 3D printer for 5 G applications, and in [38], simulations of a miniature printed circuit of a Hilbert metamaterial grating based on a CRLH antenna were carried out.

As can be seen from the works [33–38], the issues of analysis and synthesis of a digital antenna array with 32×32 elements have not been carried out simultaneously. Therefore, the scientific results obtained in the proposed work differ from the results obtained in the works [33–38].

Conclusion

Based on the use of the matrix synthesis apparatus, the article proposes a method for computer modeling, visualization, and synthesis of a digital antenna array used for transmitting and receiving signals for industrial applications. The difference in the method lies in the iterative procedure for choosing the weight function, taking into account the excess level of the side lobes of the digital antenna array. The performed numerical analysis confirmed the effectiveness of this modeling and synthesis method. For any given weight function, based on the theorems of matrix theory, the method allows you to determine the complex amplitudes of the elements of a digital antenna array. In this regard, in the course of solving the synthesis problem, a weight function was found that

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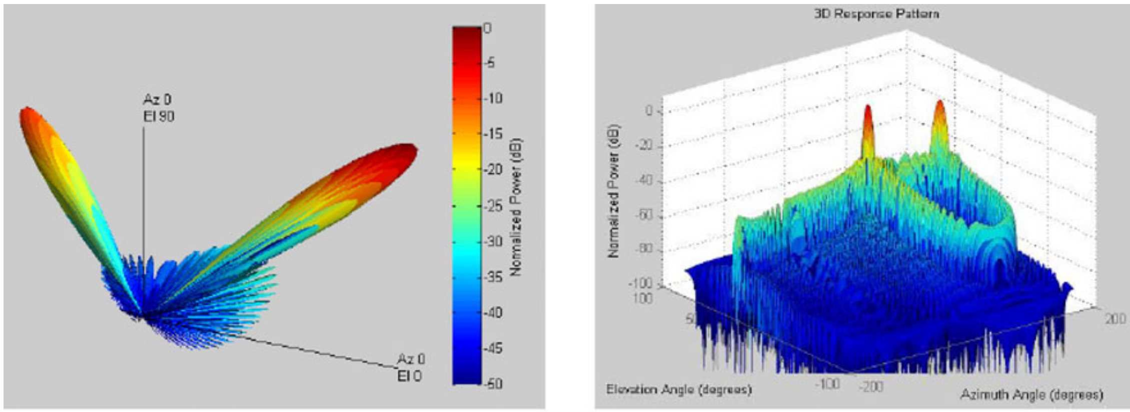

Fig. 18. Azimuth 32.5°, elevation 32.5°.

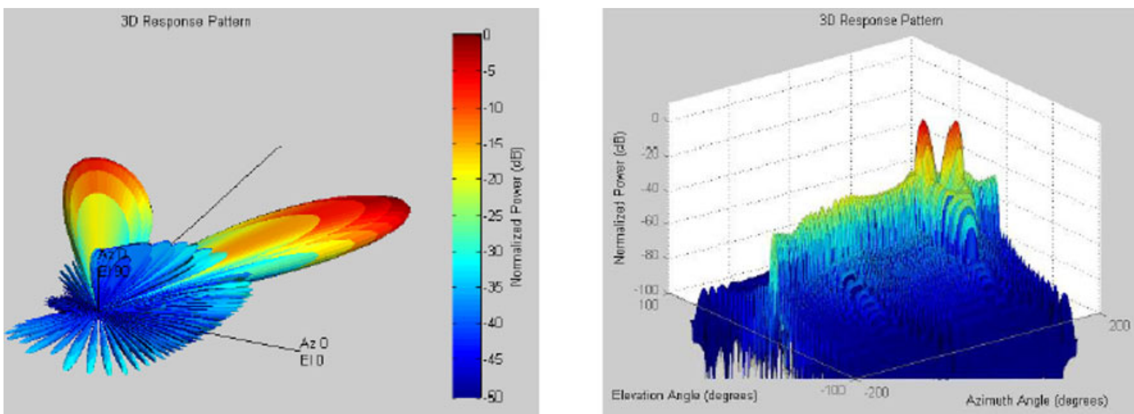

Fig. 19. Azimuth 65°, elevation 0°.

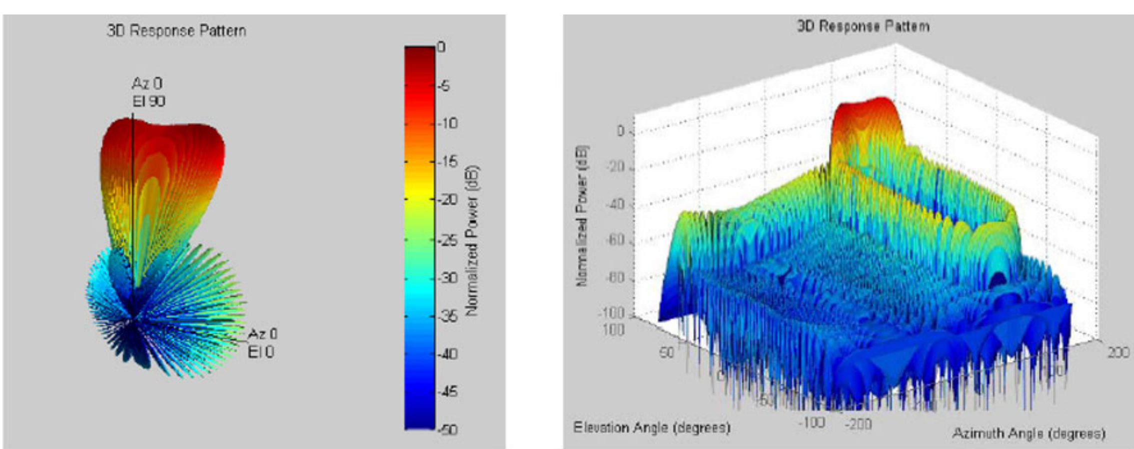

Fig. 20. Azimuth 65°, elevation 65°.

leads to the fulfillment of the requirements for radiation patterns and does not lead to a decrease in the directivity coefficient. The proposed method can be applied in the development of modern mobile antenna-feeder devices and systems with high technical and operational characteristics, as well as the development of flat diffraction antennas in the microwave and shortwave ranges, the scope of which extends from on-board systems of millimeter and submillimeter wave ranges to individual stations for receiving programs, satellite television broadcasting and radio broadcasting, and the design of low-element vibrator antenna arrays used in mobile systems for direction finding and radio monitoring of radio sources.

Data. The data that support the findings of this study are available from the corresponding author, Islam Islamov, upon reasonable request.

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