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RADIOPHYSICS

Phased Array with Controlled Directivity Pattern

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Abstract—Amplitude–phase distribution of currents in the emitters that allows independent control of the main lobe and the blind spot on the directivity pattern of the antenna where the gain substantially decreases is analyzed. The problem is solved with the aid of controlled amplitudes and phases of the waves emitted by the antenna array. The main lobe and the blind spot on the directivity pattern are formed using the synthesis of the complex amplitudes of currents in the emitters.

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INTRODUCTION

A phased array is a system of emitters in which the amplitudes and phases of currents provide the interference of the emitted wave giving rise to the total radiation field that represents a high-directivity beam. The beam direction and shape depend on the amplitude–phase distribution of currents in the emitters. Below, we consider an interesting problem of the phased-array or interference theory that represents an important radio physical problem. It involves the calculation of the amplitude–phase distribution of currents in the emitters that allows independent control of the main lobe and the blind spot on the directivity pattern in which the antenna gain significantly decreases. The solution to this problem is practically important, since it provides the suppression of the active interference source.

An antenna with a controlled directivity pattern is known as an adaptive antenna or adaptive array [1]. The directivity pattern of the adaptive array that works in the presence of interference is formed using two (main and additional) patterns. The total directivity pattern results from the subtraction of the additional pattern from the main pattern. In this case, the antenna gain substantially decreases along the direction toward the noise source [2–4]. The method necessitates the application of two simultaneously controlled arrays. Such a disadvantage is eliminated in the method that is based on a decrease in the level of the side lobes along the given direction, which can be implemented using a single array with a specific amplitude–phase distribution. Various algorithms (e.g., least mean square procedure [5, 6]) are employed for the calculation of such a distribution. The above problem of the independent control of the main lobe and the blind spot on the directivity pattern of the antenna is not a problem of the development of an adaptive array, since it does not involve the analysis of the negative feedback circuits that provide adaptation to external conditions [7]. Nevertheless, the proposed method for the formation of the blind spot at the noise direction can be used as a significant component of the integral adaptive antenna system.

The algorithms are simplified if the directivity pattern is expanded in terms of the Kotel'nikov functions (sinc functions) [8–10]. Such an array can be used in the noise-immune communication systems, radars, and GPS receivers [11].

Below, we consider a method to control the directivity pattern. The results can be employed in specific structures that work in a relatively wide frequency range.

1. ORIGINAL DISTRIBUTION OF CURRENTS AND THE CORRESPONDING DIRECTIVITY PATTERN

We consider a phased array with the current amplitude distribution in the channel separator that represents a cosine function with a pedestal (Fig. 1a):

$$I_q = \cos\left(\frac{q - \frac{M-1}{2}}{M-1}\pi\right)^2 + 0.2. \qquad (1)$$

Here, M is the number of emitters in the array and $q = 0, 1, 2, ..., M - 1$. In the calculations, we use $M = 63$ and

$$F(u) = \sum_{q=0}^{M-1}\Big[(|I_q|)\exp(i\arg(I_q)) \times \exp\Big(i2(u-u_0)\Big(q - \frac{M-1}{2}\Big)\Big)\Big]. \qquad (2)$$

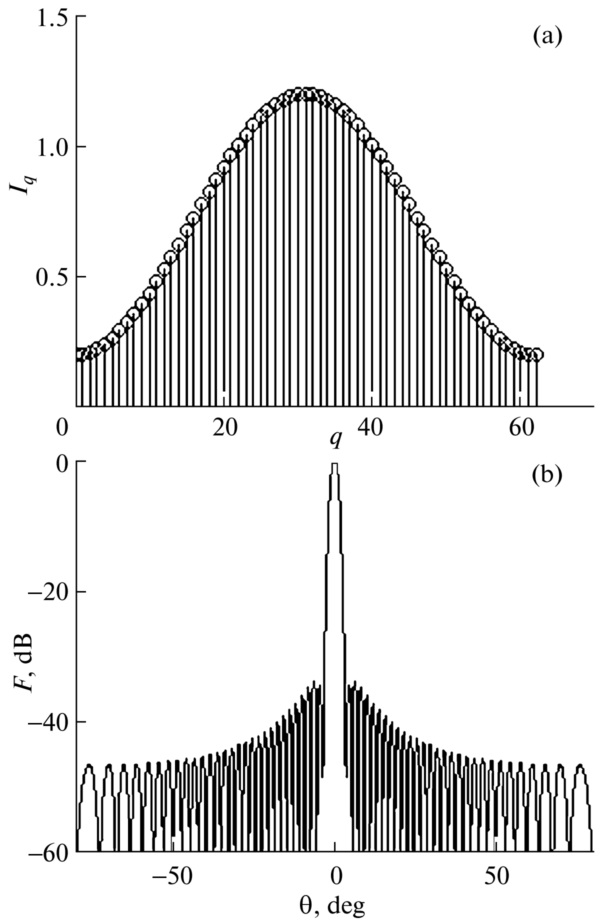

Fig. 1. Original (a) distribution of currents and (b) directivity pattern.

To simplify the representation of the directivity pattern, we use angular coordinate θ instead of generalized coordinate u:

$$u = \frac{\pi d}{\lambda}\sin\theta. \quad (3)$$

Here, d is the distance between the neighboring emitters and λ is the wavelength.

Figure 1b shows the directivity pattern as a function of coordinate θ.

2. CONTROL OF THE DIRECTIVITY PATTERN

To start the control of the directivity pattern, we fix positions of the main lobe α and blind spot β. Then, the positions are recalculated from angular coordinate θ to coordinate u using the formulas

$$u_0 = \frac{\pi d}{\lambda}\sin\alpha, \quad (4)$$

$$u_z = \frac{\pi d}{\lambda}\sin\beta. \quad (5)$$

To obtain the blind spot on the directivity pattern, we multiply function $F(u)$ by function $Z(u)$ given by

$$Z(u) = \begin{cases} a \text{ if } u_z - \frac{\delta}{2} < u < u_z + \frac{\delta}{2} \\ 1 \text{ otherwise,} \end{cases} \quad (6)$$

where $\delta = \frac{\pi d}{\lambda}\sin\gamma$ and γ is the width of the blind spot in degrees.

Parameter a determines the depth of the dip. In the absence and in the presence of the dip, parameter a is equal to and less than unity, respectively. In this work, we assume that $a = -1$.

The multiplication of expressions (2) and (6) yields a prototype of the directivity pattern with the blind spot:

$$TZ(u) = F(u)Z(u). \quad (7)$$

Note that expression (7) makes it possible to calculate both a variation in the field amplitude in the far-field zone and a phase variation when $a < 0$.

To synthesize the distribution of currents that corresponds to the directivity pattern with the blind spot (expression (7)), we employ the expansion in terms of the Kotel'nikov functions

$$\psi_p(u) = \frac{\sin(Mu - \pi p)}{Mu - \pi p}, \quad (8)$$

where variable u is given by expression (3) and M is the number of emitters in the array, which is used in formulas (1) and (2). Such functions are also known as sinc functions: Sinc(u).

The above system of functions is orthogonal and satisfies the following condition:

$$\frac{M}{\pi}\int_{-\infty}^{\infty}\frac{\sin(Mu - \pi p)}{Mu - \pi p}\frac{\sin(Mu - \pi l)}{Mu - \pi l}du = \begin{cases} 1, & p = l \\ 0, & p \neq l. \end{cases} \quad (9)$$

Consequently, the directivity pattern can be expanded in terms of the Kotel'nikov functions and represented as [7–9]

$$F(u) = \sum_{p=-\frac{M-1}{2}}^{\frac{M-1}{2}} N_p\frac{\sin(Mu - \pi p)}{Mu - \pi p}, \quad (10)$$

where N_p are Kotel'nikov samples.

Thus, the Kotel'nikov samples are calculated using the following formula:

$$N(p) = \frac{M}{\pi}\int_{-R}^{+R} TZ(u)\left(\frac{\sin(Mu - \pi p)}{Mu - \pi p}\right)du, \quad (11)$$

where $p = -31, -30, \ldots, 31$, since $M = 63$ in the case under study. For $M = 63$, the integration limits can be determined using $R = M/\pi \cong 20$. Parameter R can be estimated with the aid of integration in expression (9) with R and $-R$ as the integration limits. The calculations show that, in most cases, integral (9) differs from zero or unity by less than 10^{-3} for any integer p and l and $R = 20$.

The resulting Kotel'nikov samples are recalculated into the distribution of currents using the formula from [8]

$$I'_q = \sum_{p=-\frac{M-1}{2}}^{+\frac{M-1}{2}} N(p)\exp\left[i\pi p\left(1-\frac{1}{M}-\frac{2q}{M}\right)\right]. \quad (12)$$

Then, the distribution of the complex amplitudes of currents is used to calculate the phase shifts with the aid of the evident expression

$$\varphi'_q = \frac{180}{\pi}\arg(I'_q). \quad (13)$$

Figures 2a and 2b demonstrate the results that are calculated with formulas (12) and (13) for $\beta = 20°$ and $-20°$, respectively, and $\alpha = -30°$.

We assume that the tilted phase front of the original directivity pattern in the absence of the blind spot is given by

$$\varphi_q = -\frac{180}{\pi}(q+1)\left(\frac{2\pi d}{\lambda}\right)\sin\left(\left(\frac{\pi}{180}\right)\alpha\right). \quad (14)$$

Then, the correction that is needed for the formation of the blind spot can be calculated. The difference of the phases given by formulas (13) and (14) is written as

$$\Delta\varphi_q = (\varphi_q - \varphi'_q). \quad (15)$$

The distribution of the current amplitudes that is needed for the formation of the blind spot is determined by expression (12). The distributions of the current amplitudes given by formulas (12) and (1) can be compared:

$$K(q)_{\partial B} = 20\log(|I'_q|/I_q). \quad (16)$$

Figures 3a and 3b show the results that are calculated with the aid of formulas (15) and (16) for $\beta = 20°$ and $-20°$, respectively, $\alpha = -30°$, and the given parameters of the directivity pattern.

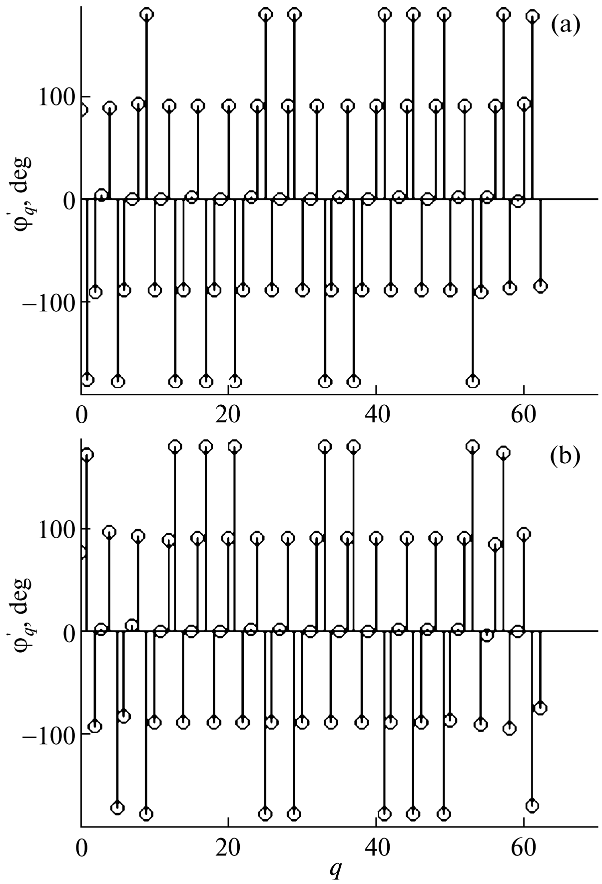

Fig. 2. Distributions of the phases of currents that are calculated using the synthesis procedure.

3. CONSTRUCTION OF THE DIRECTIVITY PATTERNS USING THE CALCULATED DISTRIBUTION OF COMPLEX CURRENTS

Using the known distribution of the complex currents, we calculate the resulting directivity pattern with the aid of the known formula

$$F^{(1)}(\theta) = \sum_{q=0}^{M-1} I'_q e^{i(kdq\sin(\theta))}, \quad (17)$$

which takes into account both phases and amplitudes of the complex currents.

Figures 4a and 4b present the directivity patterns that are calculated with formula (17) for $\beta = 20°$ and $-20°$, respectively, and $\alpha = -30°$.

Note an important advantage of the above method to control the directivity pattern of the antenna array, which is the independence of the positions of the main lobe and blind spot. The positions of the main lobe and blind spot become really independent when the crosstalk of the neighboring emitters is eliminated or substantially suppressed. A mutual coupling matrix (MCM) [7] in the power-supply circuit of the emitters is used in the existing methods for the compensation of the crosstalk. The methods for the MCM implementation can be found in [7]. In addition, note that the metamaterial elements [12] in the phased-array structure allow the suppression of the crosstalk of the neighboring emitters.

Consider the scenario in which the phases of the currents in the emitters are controlled and the original distribution of the current amplitudes in the channel separator is not corrected. In this case, the directivity pattern is calculated as

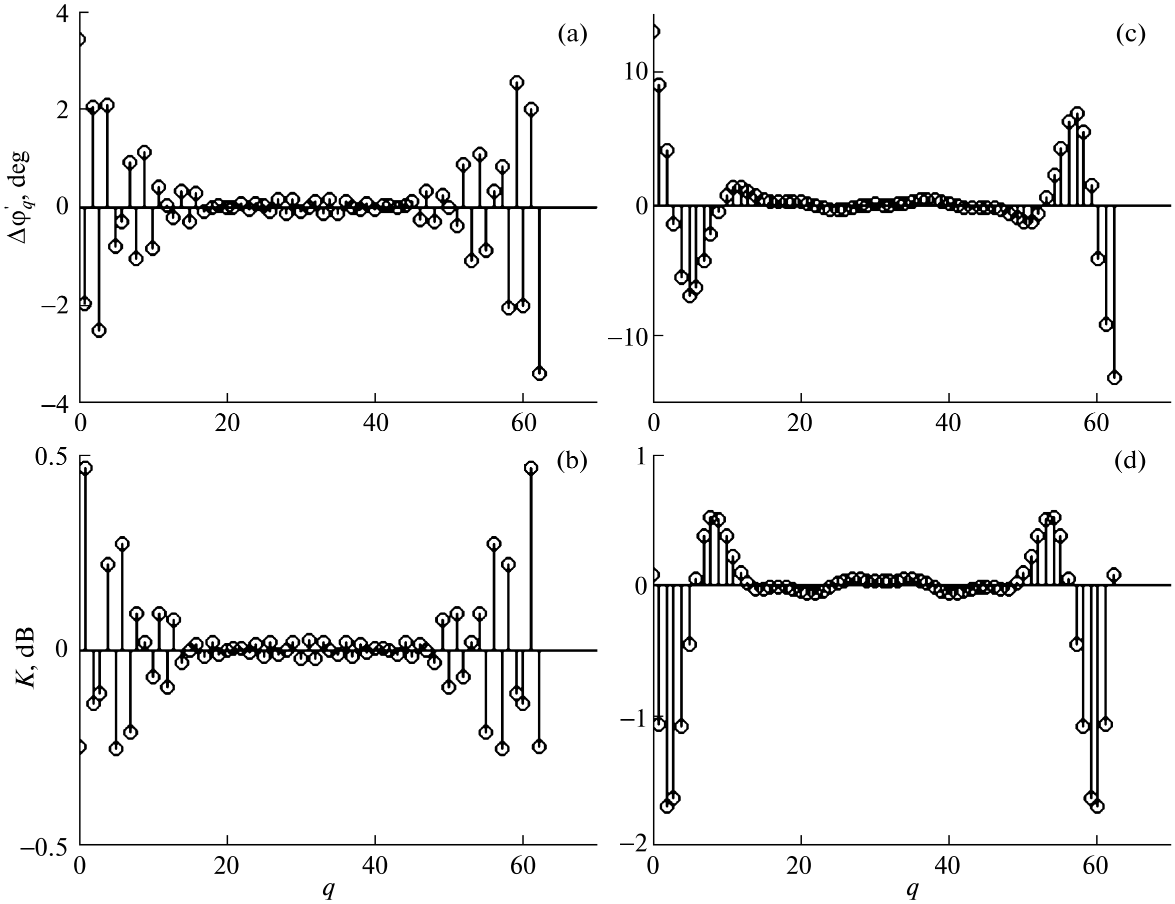

Fig. 3. Phase difference and the amplitude ratio of the currents relative to the tilted phase front and the original distribution of the current amplitudes.

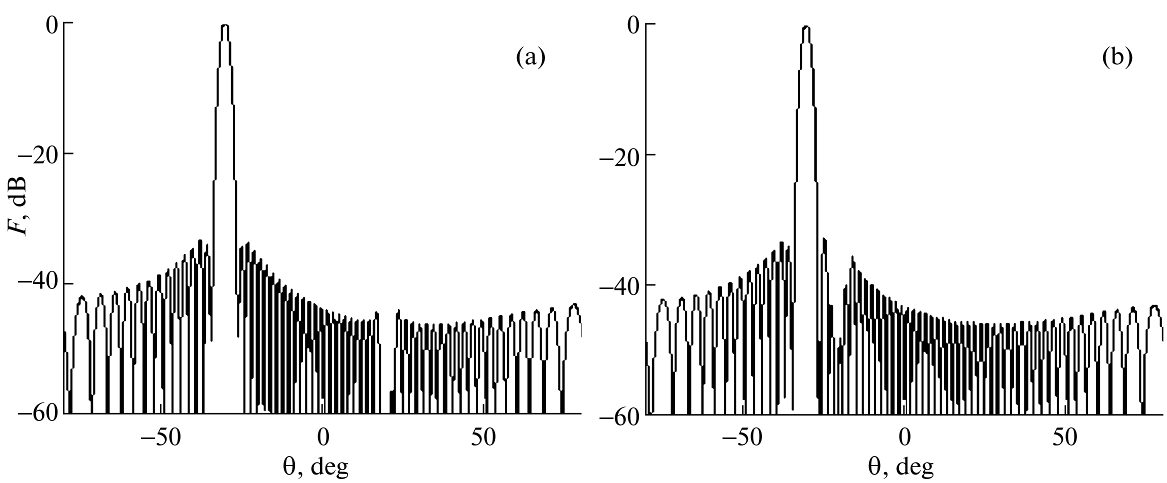

Fig. 4. Directive patterns of the phased array.

$$F^{(2)}(\theta) = \sum_{q=0}^{M-1} I_q e^{i\arg(I_q')} e^{i(kdq\sin(\theta))}. \qquad (18)$$

This formula takes into account only the phases of the complex currents and the original distribution of currents in the channel separator serves as the distribution of the current amplitudes.

CONCLUSIONS

An important radio physical problem that involves the calculation of the amplitude–phase distribution of currents in the emitters that provides the independent control of the main lobe and blind spot on the directivity pattern in which the antenna gain substantially decreases is analyzed. The solution to this problem is important for the practical applications, since it allows the suppression of the active interference. In practice, the interference of the waves that are emitted by the array is controlled. The main lobe and the blind spot are formed using the synthesis of the complex amplitudes of currents in the emitters. Also note that the synthesis employs a large amount of calculations and is time-consuming. To reduce the preparatory work that is needed for the formation of the desired directivity pattern, the corresponding distributions of the amplitudes and phases of currents in the emitters must be preliminary calculated and stored in memory of the control units of the phased array.

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