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Directivity of Multidipole Antennas in Microwave Energy Transmission Systems

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Abstract—Reception characteristics of multidipole antennas of the rectenna converters used in the microwave energy transmission systems are calculated. The effect of the number, mutual positions, and possible failures of dipole elements on the antenna pattern is investigated.

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INTRODUCTION

Progress in the field of microwave power engineering creates the basis for the design of highly efficient ground-based and spaceborne wireless energy transmission systems [1].

Antenna arrays formed from a system of dipole radiators are often considered as transmitting systems of wireless (microwave) energy transmission lines. A rectenna (rectifying antenna) containing a dipole antenna and a Schottky semiconductor diode is considered as a receiving–converting element of receiving systems. The maximum efficiency of the conversion of microwaves by a rectenna (up to 90%) is attained in optimum operating modes (1–2 W/diode), which are close to the limiting operating conditions of modern microwave Schottky diodes. This operating mode is assumed to be realized in megaprojects of space power engineering [2], in which the estimated power density of the incident radiation at the center of the receiving aperture of a ground-based system reaches 230 W/m^2. If the density of dipoles is optimal (150 dipoles per square meter at a frequency of 2.45 GHz), the load falling at one rectenna element is also close to optimal.

However, the power density substantially decreases (up to –10 dB) near the radius of the ground-based system and reaches 23 W/m^2 at the aperture edge. This decrease can substantially lower the conversion efficiency in the case of the application of single-type rectennas in all facilities of the ground-based system. A similar problem arises in the projects for the ground-based transmission of microwave energy, which must satisfy requirements of environmental safety and should be designed for an even lower power density (30 W/m^2 at the center and 3 W/m^2 at the periphery) [3, 4]. In such systems, discrepancy between the microwave power falling at one diode and the optimum operating mode of this diode becomes even larger.

One of the possible solutions to this problem is to combine several dipoles into one antenna element loaded with one microwave diode and to keep the optimum density of dipoles. Such multidipole (containing up to 20 dipoles) antenna elements are suitable for application in ground-based transmission lines with a lower level of the power density of microwave radiation.

However, the pattern of multidipole antenna elements may differ substantially from the pattern of a half-wave dipole antenna used in conventional rectennas. This circumstance may have a substantial effect on the resulting energy characteristics of microwave transmission lines and requires an additional analysis. The effect of some other factors (the number of dipoles in an antenna element, configuration and mutual positions of these elements, failures of some dipoles, etc.) should also be considered. Recently developed finite-difference methods for the modeling of electromagnetic problems on the basis of direct solution of the Maxwell equations enable the analysis of this problem.

1. A METHOD FOR CALCULATING THE CHARACTERISTICS OF MULTIDIPOLE ANTENNAS

For the analysis of the characteristics of multidipole antenna elements, we use a method based on discretization of the integral form of the Maxwell equations written in the space–time representation [5, 6]:

$$\oint_{\partial A} \mathbf{E} d\mathbf{s} = -\int_A \frac{\partial \mathbf{B}}{\partial t} d\mathbf{A}, \quad (1)$$

$$\oint_{\partial A} \mathbf{H} d\mathbf{s} = \int_A \left(\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}\right) d\mathbf{A}, \quad (2)$$

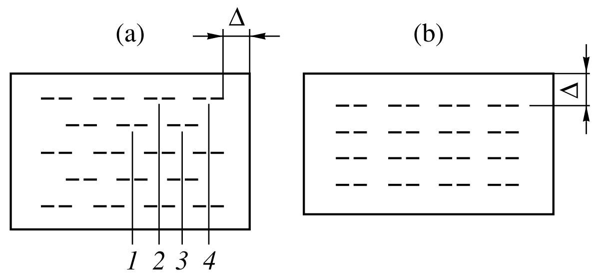

Fig. 1. Positions of dipoles in (a) triangular and (b) rectangular multidipole antennas: Δ is the length of the prominent part of the conducting surface and *1*, *2*, *3*, and *4* are the numbers of columns of dipoles in the array.

$$\oint_{\partial V} \mathbf{D} d\mathbf{A} = \int_V \rho dV, \quad (3)$$

$$\oint_{\partial V} \mathbf{B} d\mathbf{A} = 0, \quad (4)$$

where $\mathbf{E}(r, t) = \mathbf{E}(r)e^{j\omega t}$, $\mathbf{H}(r, t) = \mathbf{H}(r)e^{j\omega t}$, $\mathbf{D}(r, t) = \mathbf{D}(r)e^{j\omega t}$, and $\mathbf{B}(r, t) = \mathbf{B}(r)e^{j\omega t}$ are the vectors of intensity and induction of the electric and magnetic fields and V and A are the spatial domain and the surface of this domain, respectively.

For the numerical solution of Eqs. (1)–(4), domain V is divided into a set of cells (mesh) and a secondary mesh is formed in the direction orthogonal to the plane of the primary mesh of cells. Here, the distributions of the components of electric intensity **e** and electric induction **d** are localized on the primary mesh and the distributions of the components of magnetic intensity **h** and magnetic induction **b** are localized on the secondary mesh.

Taking into account the Faraday law, we find that the contour integral on the left-hand side of Eq. (1) can be written with a sufficient accuracy as a sum of four voltages **e** at the mesh nodes and the time derivative of the magnetic induction calculated on the primary mesh is the integrand appearing on the right-hand side of this equation:

$$e_i + e_j - e_k - e_l = -\frac{\partial}{\partial t} b_n. \quad (5)$$

Repeating this procedure for all accessible cells of the primary mesh, we arrive at the following matrix formulation of the calculation scheme of Eq. (1):

$$Ce = -\frac{d}{dt} b, \quad (6)$$

where C is the discrete matrix operator consisting of elements 0, 1, and –1.

The matrix formulation of Eq. (2) for the secondary mesh can be obtained in a similar way:

$$\tilde{C}h = \frac{d}{dt} d + j, \quad (7)$$

where $\tilde{C}$ is an analogous discrete matrix operator.

In order to obtain discrete forms of Eqs. (3) and (4), it is convenient to introduce discrete divergence operators S and $\tilde{S}$ related to the primary and the secondary mesh, respectively:

$$\tilde{S}d = q, \quad (8)$$

$$Sb = 0. \quad (9)$$

Finally, relationships between intensities of the electric and magnetic fields and values of the electric and magnetic inductions can be used to equate integral values of these quantities at the cell faces. The resulting coefficients, whose values depend on the averaged constitutive parameters and the spatial resolution of the mesh, can be combined into corresponding matrices $\mathbf{M}_\varepsilon$, $\mathbf{M}_\mu$, and $\mathbf{M}_\sigma$:

$$d = M_\varepsilon e, \quad (10)$$

$$b = M_\mu h, \quad (11)$$

$$j = M_\sigma e + j_s. \quad (12)$$

Following this way, we can obtain all matrix equations of type (6)–(12) necessary for solving electromagnetic field problems in a discrete mesh space.

The initial and boundary conditions that should be set in this mesh domain depend on a particular design of multidipole antennas.

In numerical experiments, we calculated the pattern of multidipole antennas $K(\theta) = 4\pi P_\theta P_0^{-1}$ and the reception efficiency $\mathrm{Eff} = (P_0 - P_p)P_0^{-1}$, where P_0 is the total power, P_θ is the power radiated within a unit angle, and P_p is the power of the radiation loss in the multidipole antenna.

2. NUMERICAL RESULTS

We investigated two types of dipole antenna arrays with different numbers of elements. The antennas were designed for operation in rectenna converters at a frequency of 2.45 GHz. Features of multidipole antennas with triangular (Fig. 1a) and rectangular (Fig. 1b) arrangements of dipoles were studied.

In "triangular" antenna arrays containing 5 and 18 elements (Fig. 1a), dipoles are placed at the vertices of an equilateral triangle with a spacing of 0.64λ. In "rectangular" antenna arrays containing 9 and 16 elements (Fig. 1b), the horizontal spacing between the dipoles is 0.75λ. The vertical spacing between the rows of dipoles is equal to 0.25λ. It is assumed that individ-

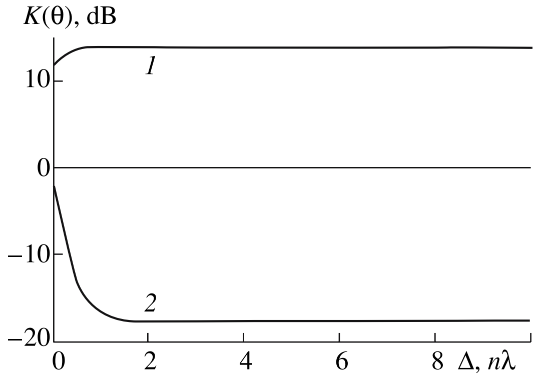

Fig. 2. Dependence of the array directivity in the (curve *1*) forward and (curve *2*) backward directions for a 5-element dipole array with a triangular arrangement of dipoles (see variant (a) in Fig. 1) vs. length Δ of the prominent part of the conducting reflector.

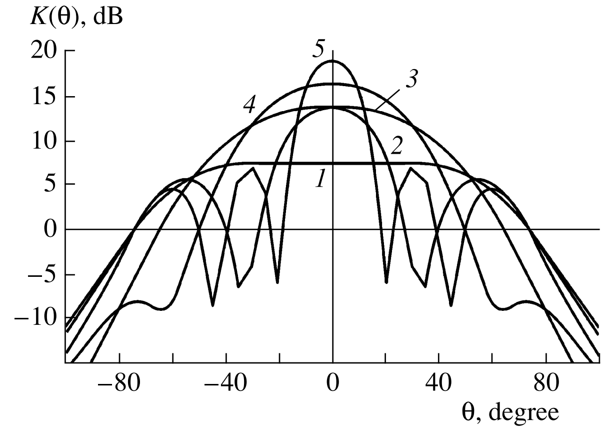

Fig. 3. Patterns of dipole antenna arrays in the plane $\varphi = 90°$ for the normal incidence of microwave radiation. Curves *1–5* correspond, respectively, to an isolated dipole, an array of 5 dipoles, an array of 9 dipoles, an array of 16 dipoles, and an array of 18 dipoles.

ual dipoles are connected by microstrip lines so that the radiation incident along the normal and received by these dipoles is summed up in phase.[1]

A metal reflector, which improves the efficiency of the rectenna converter, is placed under the dipole antenna array at a distance of 0.25λ from the array plane.

The effect of the prominent part of the conducting reflector, which protrudes by length Δ beyond the outer contour of the dipole antennas, on the gain of a multidipole antenna array was investigated (see Fig. 2). Calculations have shown that, if length Δ of the protruding part exceeds 2λ, it has only a slight effect on the antenna directivity in the forward and backward directions and on the level of the pattern sidelobes. Therefore, it is expedient to limit the length of the prominent part and, in the subsequent calculations, we used $\Delta = 2\lambda$.

In order to study the effect of the number and mutual positions of the array dipoles, we calculated patterns of the aforementioned antenna arrays in the conditions of normal and oblique incidence of microwave radiation onto the rectenna plane.

Figures 3 and 4 show patterns of antenna arrays in the planes $\varphi = 0°$ and 90° for the normal incidence of microwave radiation.

As the number of dipoles increases, the directivity of the multidipole antenna also increases and reaches 19 dB for a triangular array containing 18 dipoles. The efficiency of antenna arrays with a triangular arrangement of dipoles is substantially higher than the efficiency of arrays with a rectangular arrangement of dipoles.

An increase in the number of dipoles causes substantial narrowing of the antenna pattern (to 18° in the plane $\varphi = 90°$ and 20° in the plane $\varphi = 0°$ for a triangular array of 18 dipoles). In the case of an isolated dipole antenna, the pattern beamwidth exceeds 120° in the plane $\varphi = 90°$ and 80° in the plane $\varphi = 0°$. Note that, in the plane $\varphi = 90°$, patterns of arrays with a rectangular arrangement of dipoles are substantially wider than the pattern of triangular arrays. At the same time, in the plane $\varphi = 0°$, patterns of rectangular arrays are very narrow, 14°–20° for the considered variants. In contrast, patterns of triangular arrays in the plane $\varphi = 0°$ are wider than patterns in the plane $\varphi = 90°$. This difference becomes smaller as the number of dipoles increases (see Table 1).

In the case of oblique incidence of microwave radiation onto a multidipole antenna, the antenna pattern

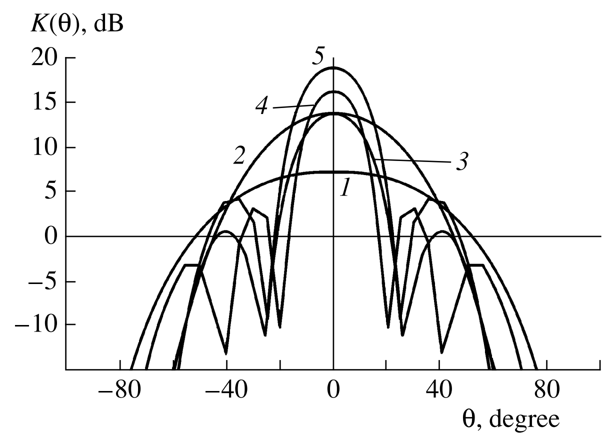

Fig. 4. Patterns of dipole antenna arrays in the plane $\varphi = 0°$ for the normal incidence of microwave radiation. Curves *1–5* correspond, respectively, to an isolated dipole, an array of 5 dipoles, an array of 9 dipoles, an array of 16 dipoles, and an array of 18 dipoles.

[1] Calculation of the parameters of connecting microstrip lines is a relatively solvable problem, which lies beyond the scope of this paper.

Table 1. Characteristics of multidipole arrays

	Multidipole rectenna converter			
Configuration	Triangular		Rectangular	
Number of dipoles	5 dipoles	18 dipoles	9 dipoles	16 dipoles
Efficiency	0.98	0.97	0.86	0.84
Directivity, dB	13.7	19.1	13.9	16.4
Pattern beamwidth				
in the plane φ = 90°	22	18	62	46
in the plane φ = 0°	42	20	20	14

Table 2. Effect of failures in a multidipole antenna

Configuration	Triangular, 18 dipoles				
Failures of dipoles	No	Column 1	Column 2	Column 3	Column 4
Directivity, dB	19.1	18.1	17.9	18.2	17.8
Pattern beamwidth					
in the plane φ = 90°	18	19.2	20.2	19.3	20.3
in the plane φ = 0°	20	21.6	22.5	21.7	22.4

becomes asymmetric (see Fig. 5). The pattern maximum shifts towards the incident radiation and the level of the main lobe gradually decreases, in contrast to variations in the sidelobe level. If the angle of incidence is 30°, the backlobe level reaches 10 dB and becomes only 6 dB lower than the level of the main lobe.

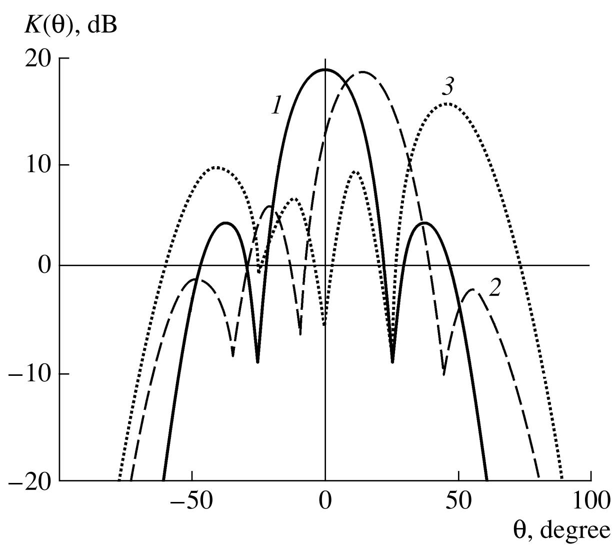

Fig. 5. The pattern in the plane φ = 0° of a triangular antenna array containing 18 dipoles for the case of oblique incidence of microwave radiation. Curves *1–3* correspond, respectively, to the normal incidence, an angle of incidence of 75°, and an angle of incidence of 30°.

3. EFFECT OF DIPOLE FAILURES

The effect of possible failures of different dipole columns in a triangular array of 18 elements on the shape and symmetry of the array pattern was investigated. The results of the calculation have shown (see Table 2) that failure of a lateral column (no. 2, 3, or 4, see Fig. 1) causes only slight lowering of the array directivity (by 1–2 dB) and widening of the main lobe in the planes φ = 90° and 0° (by 10–20%). In addition, the array pattern becomes slightly asymmetric. Failure of the center column of dipoles (no. 1, see Fig. 1) does not break the pattern symmetry and only slightly lowers the pattern magnitude.

The effect of such failures becomes more pronounced for the arrays containing smaller numbers of dipole elements.

CONCLUSIONS

Application of multidipole antennas in rectenna elements is most expedient for ground-based microwave energy transmission lines with an environmentally safe level of the power density of microwave radiation. The number of dipoles in a rectenna element can vary from 5 at the center of the receiving system to 20 at the edge. In this case, the operating mode of the rectifying diode in the rectenna element will be close to optimal.

Triangular arrangement of dipoles is more efficient and offers higher directivity than a rectangular configuration. Possible failures of individual columns of dipoles in the considered variants of multidipole antennas can slightly lower the array directivity (by 1–2 dB) and widen the main lobe (by 10–20%).

In the practical design of ground-based microwave energy transmission systems, one should take into account that the pattern of a multidipole antenna can differ substantially from the pattern of an isolated dipole element. Narrowing of the pattern beamwidth by a factor of 4–5 requires more accurate positioning and adjustment of transmitting and receiving systems.

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