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Some results of application of helical radiators in linear antenna arrays for shaping flat-topped radiation patterns

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Electrodynamical modeling of linear antenna arrays consisting of three and five cylindrical helical radiators is carried out. The modeling includes optimization of the radiator geometrical parameters aimed at shaping flat-topped (sectorial) array element radiation patterns with providing low return loss. Some results characterizing sufficiently high quality of the flat-topped radiation patterns in the frequency band 2.7−2.9 GHz at element spacing 0.9−1.1 of wavelength, as well as influence of array edges on the element radiation pattern shape are presented.

Keywords: Helical radiators, phased antenna arrays, flat-topped radiation patterns.

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The problem of shaping flat-topped radiation patterns (RPs) of an element in linear and planar phased antenna arrays designed for scanning in a limited sector remains highly relevant. The solution to this problem will allow either providing a given array gain in a given scanning area with a minimum number of expensive controlled elements or maximizing the gain in a scanning area that is as wide as possible for a given element spacing. Various approaches to solving the indicated problem and the results obtained using these approaches were discussed in books [1,2] and in numerous journal and conference publications. Recent results and references to other recent studies revealing current interest in the topic may be found in [3–5].

One of the approaches to shaping flat-topped RPs of array elements involves the use of end-fire radiating elements, such as protruding dielectric rods, multi-disk radiators, and director radiators [1]. It is known (see, e. g., [6]) that cylindrical helical antennas may also support an end-fire (axial) radiation mode. Helical radiators are used as elements of antenna arrays due to their relatively simple and lightweight design, low cost, and capability of operating within a relatively wide frequency band [7–9]. However, a review of the literature shows that shaping flat-topped radiation patterns in such arrays has not been discussed, although a helical antenna was proposed in [10] to be used in an array designed for scanning in a limited spatial region.

The aim of the present study is to report novel data characterizing capability of the helical radiators to shape flat-topped radiation patterns of an element in linear phased antenna arrays designed for scanning in a limited sector.

These results were obtained by numerical simulation of a linear array in the well-known CST Studio Suite package using the Frequency Domain Solver with adaptive mesh refinement with a maximum cell size equal to 1/6 of the wavelength (six cells per wavelength). One of the models is shown in Fig. 1. The radiator contains a cylindrical wire helix excited through a 50 Ω coaxial line. This helix protrudes from a coaxial metal cylinder mounted on the screen. Input matching of the helix is provided by a thin metal plate attached to the wire (see Fig. 1).

As it is known (see, e. g., [6]), the axial radiation mode of a helix is provided when the $3\lambda/4 < C < 4\lambda/3$ condition is met. Here, C is the perimeter of a circle determined by helix diameter D ($C = \pi D$) and λ is the wavelength in free space. In addition, winding angle $\alpha = \arctan(S/C)$, where S is the distance between adjacent turns, must satisfy condition $12^\circ < \alpha < 14^\circ$. At least five turns are normally used for providing the axial mode.

The array shown in Fig. 1 consists of three helical radiators positioned on a perfectly conducting screen with element spacing d_x along the x axis. It is assumed that only the input of the central element is excited and the inputs of other elements are connected to matched loads. This corresponds exactly to the conditions under which the RP of an array element is defined.

The array element parameters were optimized at central frequency of 2.8 GHz ($\lambda \approx 107.14$ mm) with $d_x = 0.9\lambda$ and a wire diameter of 2 mm ($\approx 0.019\lambda$). The following values of other radiator parameters were chosen as a result: number of turns $N = 9$, circle perimeter $C = \lambda$, a matching plate width of 8.3 mm ($\approx 0.077\lambda$), a plate length of 25.7 mm (0.24λ), a plate thickness of 0.5 mm (0.005λ), a distance from the lower edge of the plate to the screen of 2.6 mm, a cylinder diameter of 81.8 mm ($\approx 0.76\lambda$), and a cylinder height of 34 mm ($\approx 0.317\lambda$).

Modeling of the structure with different numbers of turns N has shown that the flat RP top is kept if N does not exceed 12. This is illustrated in Fig. 2, a, where the RP of

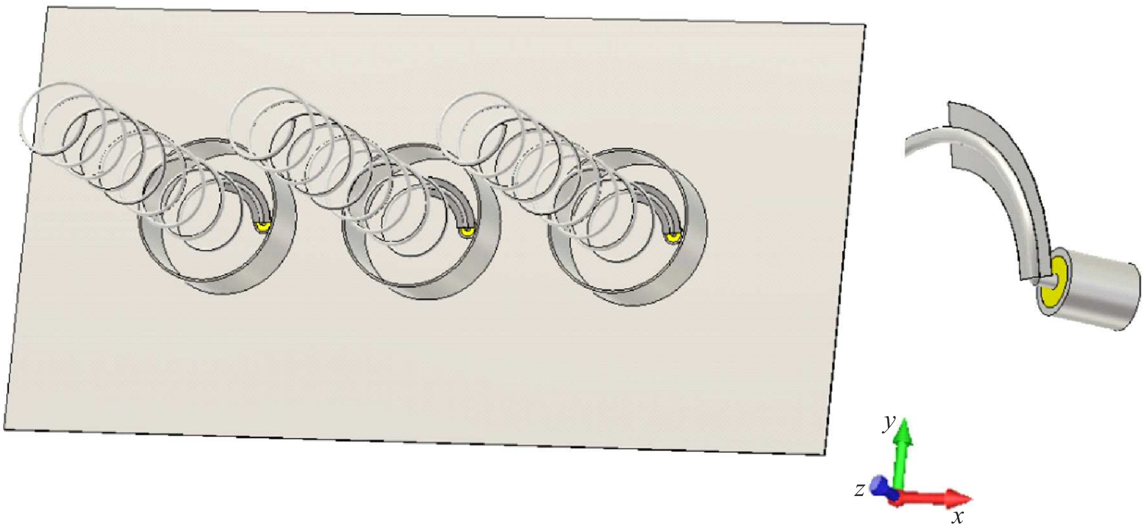

Figure 1. Linear array of three helical radiators and matching plate geometry (right).

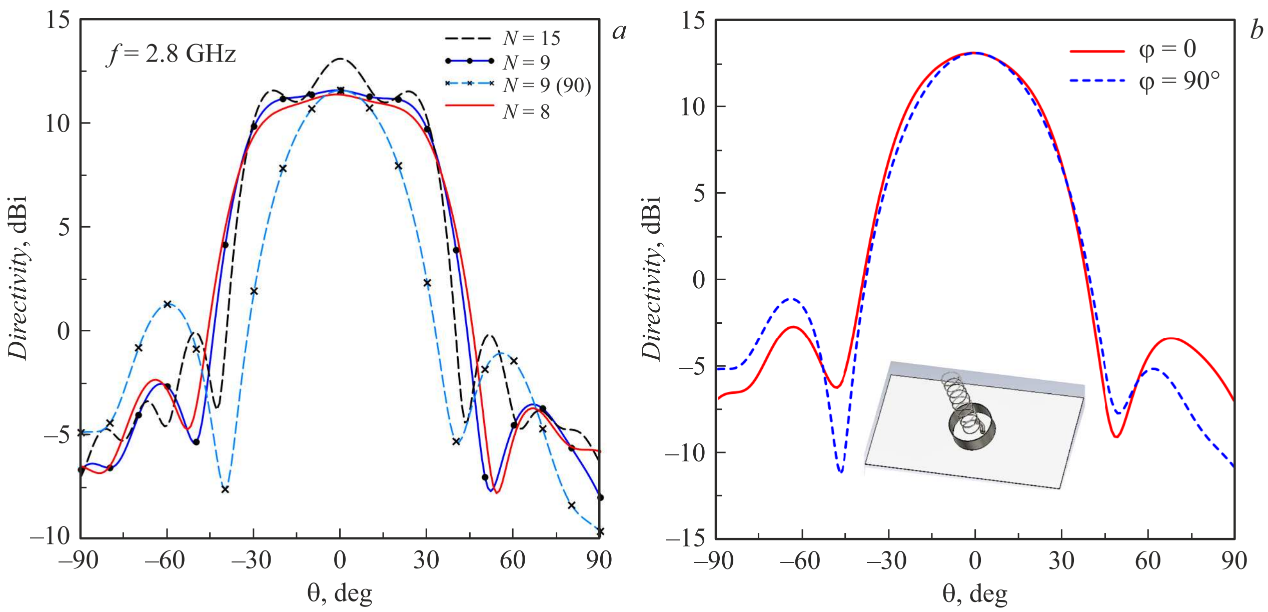

Figure 2. RP of the central element of the array with different numbers of turns N (a) and RP of a single helical radiator in planes $0xz$ ($\varphi = 0$) and $0yz$ ($\varphi = 90^\circ$) at $N = 9$ (b) at frequency of 2.8 GHz.

the central array element at the central frequency is plotted at different values of N. The results show that the shape of the pattern differs significantly from the desired one at high N values. A sectorial shape may be maintained at $N < 9$, but at a somewhat reduced level. The radiation pattern of a single radiator with the parameters listed above is presented in Fig. 2, b for comparison and will be used in subsequent analysis.

The flat-topped RP corresponding to the parameters specified above has a half-width of $\approx 29^\circ$ at the level of -1 dB. The results of calculation of the element RP at frequencies of 2.7, 2.8, and 2.9 GHz shown in Fig. 3, a show that the sectorial RP shape is kepr within a frequency range of approximately ± 4 % without significant changes in the level of the flat top and side lobes. The vertical dashed lines in Fig. 3, a correspond to the edges of the ideal sectorial radiation pattern [1] with half-width $\theta_{\max} = \arcsin(\lambda_0/2d_x) \approx 33.75^\circ$ at the central frequency. Figure 3, b demonstrates a dependence of the axial ratio on the observation angle in the principal planes. The behavior of the reflection coefficient (parameter S_{11}), which characterizes the matching of an array element in an array within a frequency band, is shown in Fig. 3, c by the curve with circles. The indicated coefficient is compared with the reflection coefficient of a single helical radiator (solid curve). The dashed curve (parameter S_{21}) demonstrates that the

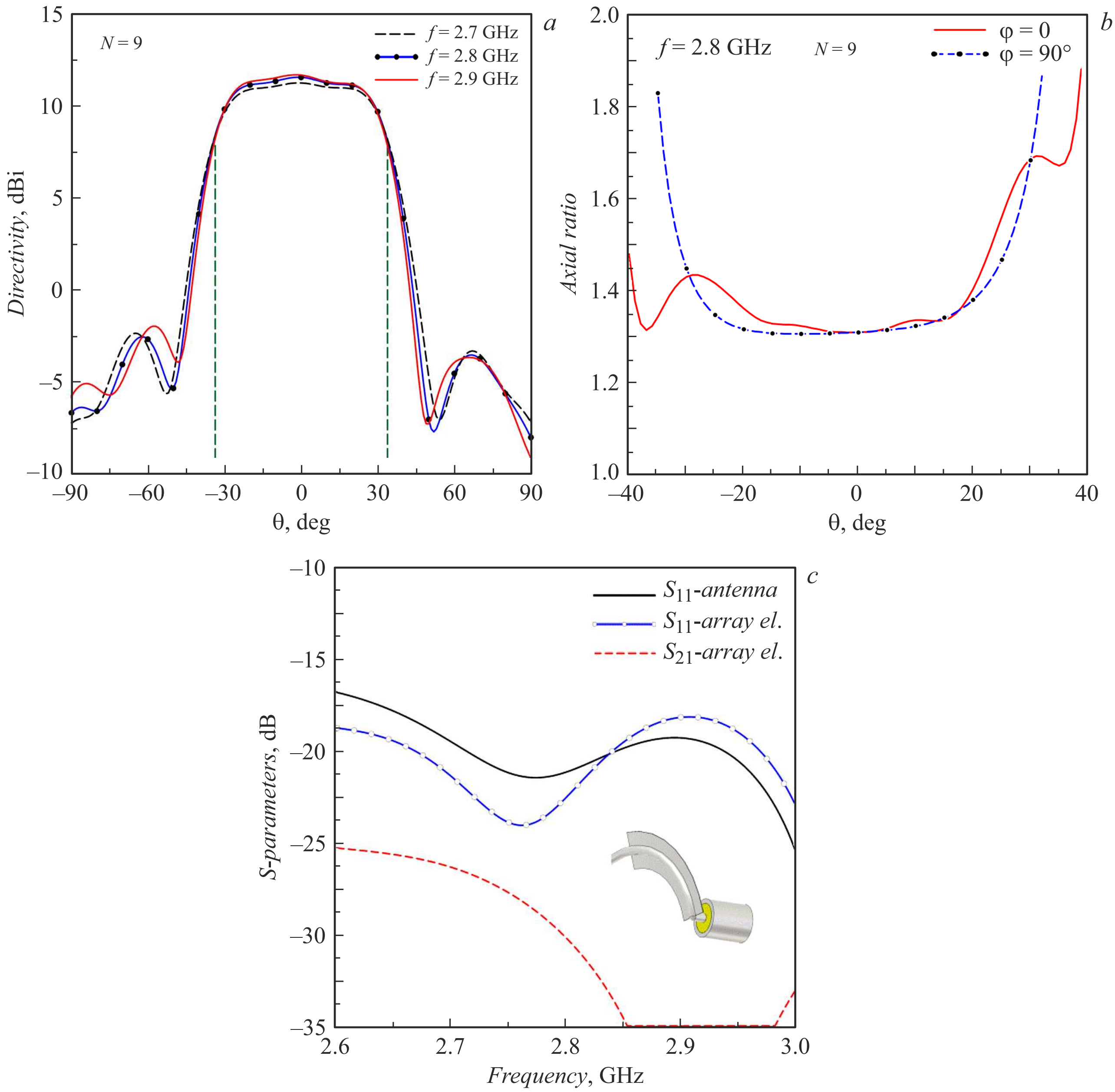

Figure 3. RP of a three-radiator array element at different frequencies (a), axial ratio in the principal planes at a frequency of 2.8 GHz (b), and comparison of S-parameters in the frequency band (c).

level of mutual input coupling between the radiators is very low.

It is of interest to compare the gain of the helical array element in the flat top region obtained as a result of the optimization with the maximum achievable gain (G_m) corresponding to the case under consideration. This quantity can be determined as $G_m = 4\pi A_m/\lambda^2$, where A_m is the maximum effective area, which corresponds to the area of an equivalent flat aperture with a uniform amplitude-phase distribution, per one array element. Since the size of the specified aperture along the array is limited by the array period d_x, the aperture area can be determined as $A_m = d_x d_m$, where d_m is the maximum transverse size of the aperture. The indicated maximum size is proposed to be determined using the gain of a single helical element shown in Fig. 2, *b*. The effective area of the indicated element can be determined as $A_{eff} = G_0\lambda^2/(4\pi)$, where G_0 is the directive gain of a single element at the maximum. The results presented in Fig. 2, *b* demonstrate that the radiation patterns of a single helical element in orthogonal planes are practically identical. Thus, it can be assumed that the equivalent aperture is square. Its effective area can then be determined as $A_{eff} = d^2$, where d is the side of the square. Since the gain of a single helical element at maximum

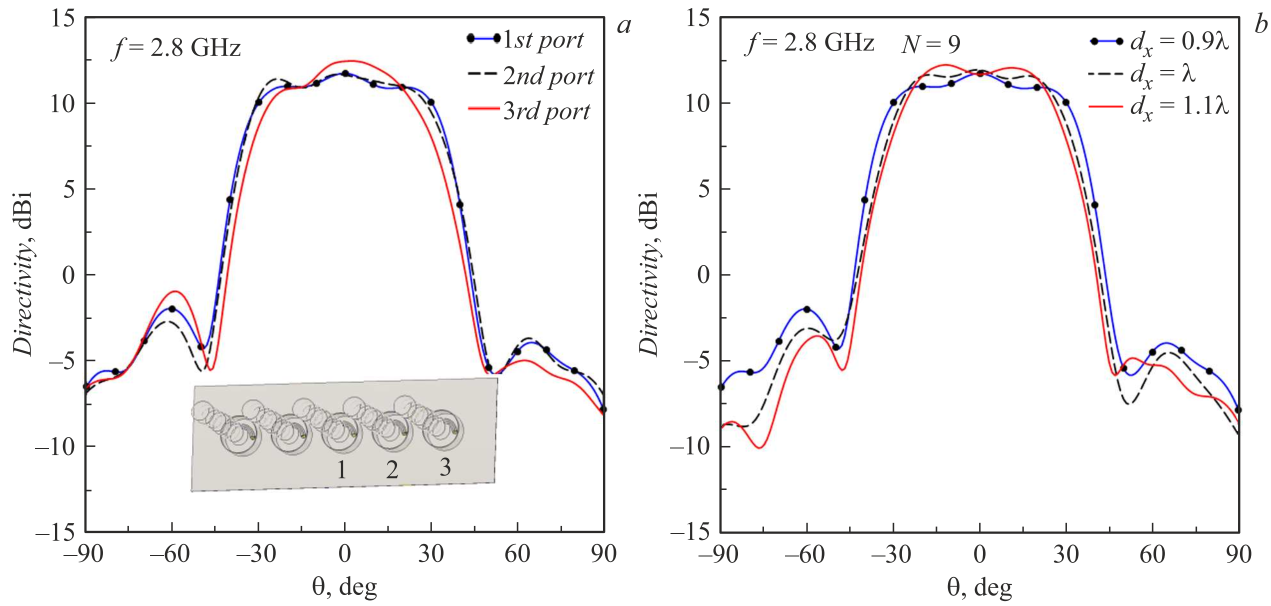

Figure 4. RPs of the central, adjacent, and outermost elements of an array of five radiators with $d_x = 0.9\lambda$ (a) and RP of the central element in a five-element array with different element spacing (b).

is, according to Fig. 2, *b*, 12.97 dB or $G_0 \approx 19.8153$, we find $d \approx 1.2557\lambda$. The obtained size is proposed to be regarded as the maximum effective transverse size of the radiator in the array; i.e., $d_m = d$. Using this, we find $A_m = d_x d_m = 1.035\lambda^2$ and, consequently, $G_m \approx 14.2013$ or 11.5233 dB. A comparison of the obtained value with the level of the flat top of the element RP (11.52 dB at frequency of 2.8 GHz; see Figs. 2, *a* and 3, *a*) shows that the gain of the helical element in the array is $\approx 100\,\%$ of the estimated maximum gain value; i.e., the efficiency of shaping this flat-topped RP is quite high.

Since the sectorial RPs of an array element are formed by means of overlapping subarrays [1,2], the shape of the RPs of the elements located at the edges or near the edges of an array can differ significantly from the RPs of the elements located more far from the edges. The edge effects were studied here using a five-element array with geometric parameters of the helical element being the same as those used in the three-element array. The results of RP calculations for the array with period $d_x = 0.9\lambda$ corresponding to excitation of the central element (first port), the neighboring element (second port), and the outermost element (third port) at frequency of 2.8 GHz are shown in Fig. 4, *a*. The results show that the RPs of the central and neighboring elements have sectorial shapes that differ only slightly from each other. The RP of the outermost element deviates more significantly from the sectorial shape. Thus, just as in the other studies dealing with the shaping sectorial RPs with end-fire radiating elements [1], the nesessary free-space coupling is provided between adjacent elements only.

The RP of the central element in the five-element array with $d_x = 0.9\lambda$ is compared in Fig. 4, *b* to the RP of the central element of the array with periods $d_x = \lambda$ and 1.1λ. The results demonstrate that when the array period increases to the specified levels, the sectorial shape does not deteriorate in any significant way; the flat top just becomes narrower and higher in level, which agrees with the known dependence of the width of a sectorial RP of an element on the array period [1,2].

Thus, novel results characterizing the efficiency of application of cylindrical helical elements in the synthesis of flat-topped sectorial radiation patterns in linear antenna arrays designed for scanning within a limited sector were presented. The results obtained by numerical electrodynamic modeling, which included optimization of geometric parameters of three- and five-element arrays in the well-known CST Studio Suite package, revealed the possibility of synthesis of sectoral radiation patterns of sufficiently high quality within the frequency band of 2.7–2.9 GHz with an element spacing of 0.9–1.1 of the wavelength. In addition, the study of the influence of the array edges on the shape of the element radiation pattern demonstrated that the free-space coupling required for shaping sectorial patterns is established between adjacent elements only.

The obtained results allow to conclude that further studies in the direction of the use of helical elements of other design, including bifilar or quadrifilar helixes and helixes with smoothly varying diameter of turns, as well as the use of helical elements in planar antenna arrays continue to stay promising.

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Conflict of interest

The authors declare that they have no conflict of interest.

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