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Modeling of Dolph–Chebyshev antenna arrays

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The design of the linear Dolph–Chebyshev antenna array for the frequency range from 24 to 26.5 GHz is presented. The geometric parameters of the antenna are optimized using Altair FEKO and the optimized antenna provides a higher gain and a low level of side lobes compared to a homogeneous linear antenna array. Broadband matching of the input impedance of the antenna array with the feed line is performed using a smooth non-uniform microstrip line, the width of which varies exponentially.

Keywords: Dolph–Chebyshev antenna array, radiation pattern, reflection coefficient

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Fifth-generation communication systems, which allow for higher data transfer rates up to 20 Gbit/s and for service receiver motion velocities up to 500 km/h (a velocity 10 times higher than the one specified in the 4G standard), are advancing rapidly at present. Their response delay is less than 0.5 ms, and the number of active service receivers is 100,000. Thus, the performance of communication systems is improved by an order of magnitude. The new standard is applied in unmanned vehicle control systems, unmanned aerial vehicles, and medicine (monitoring, remote surgery with the use of robotic platforms). In Russia, the „5G sub-6 GHz“ frequency range extending to 6 GHz (macrocells) and „5G mmWave“ frequencies above 24 GHz (e.g., the 24.5–27.5 GHz range; microcells, femtocells, and picocells) are used for 5G communication systems. An increase in the operating frequency of communication systems leads to a reduction in the dimensions of antennas, which expands the opportunities for application of MIMO antenna arrays and adaptive antenna arrays with a dynamic radiation pattern that changes depending on the signal-to-noise ratio and propagation conditions.

Since a wide-scale implementation of the 5G standard within the 24.5–27.5 GHz range, which includes the deployment of communication systems based on microcells, femtocells, and picocells (according to literature data, approximately 4.5 million cells are to be created by 2025 [1]) is expected, fairly strict requirements are imposed on the antennas used for signal reception and transmission [2–6]. As the operating frequencies used for 5G rise, signal propagation losses increase significantly, which may contribute to the degradation of quality of signal transmission due to multipath propagation phenomena. However, this limitation may also be regarded as an advantage, since the electromagnetic compatibility requirements associated with simultaneous operation of various systems are relaxed somewhat. The cell size may be increased by increasing the transmitter power or antenna gain.

In the present study, the design of an antenna array with the current distribution in it based on the properties of Chebyshev polynomials is examined. This design was proposed in [2] and provides an optimum ratio between the beamwidth and the side lobe level of the radiation pattern. The electrophysical parameters of the substrate and its thickness are chosen with account for the required operating band of the antenna and the resulting surface currents. It is known that the operating band expands with increasing thickness and decreasing permittivity; at the same time, an increase in thickness translates into a more significant contribution of emerging surface waves.

A Chebyshev array is an antenna system in which the dimensions of array elements are related to Chebyshev polynomials. This ensures a low level of side radiation and greater bandwidth and better directivity characteristics than those typical of an array of identical elements. The discussed antenna is designed to operate within the frequency range of 24.0–26.5 GHz. The antenna array has eight elements, is symmetrical, has a series power supply circuit, and fourth-order Chebyshev polynomials specify the geometric dimensions of its elements:

$$T_4(x) = 8x^4 - 8x^2 + 1,$$

where $T_m(x)$ is a Chebyshev polynomial, $x = \cos(mu)$, $-1 \leqslant x \leqslant 1$.

For an even number of radiators, currents may be written in terms of the side lobe level and the main-lobe beam width of the radiation pattern:

$$I_m = \sum_{k=m}^{N} (-1)^{N-k} \frac{B^{2k-1}(2N-1)(k+N-2)!}{(k-m)!(k+m-1)!(N-k)!},$$

$B = \mathrm{ch}(\mathrm{arch}(q^{-1})/p)$, p is the degree of a Chebyshev polynomial, q is the side lobe level, and m is the radiator number. The conductivity of radiators is related to their width and the currents.

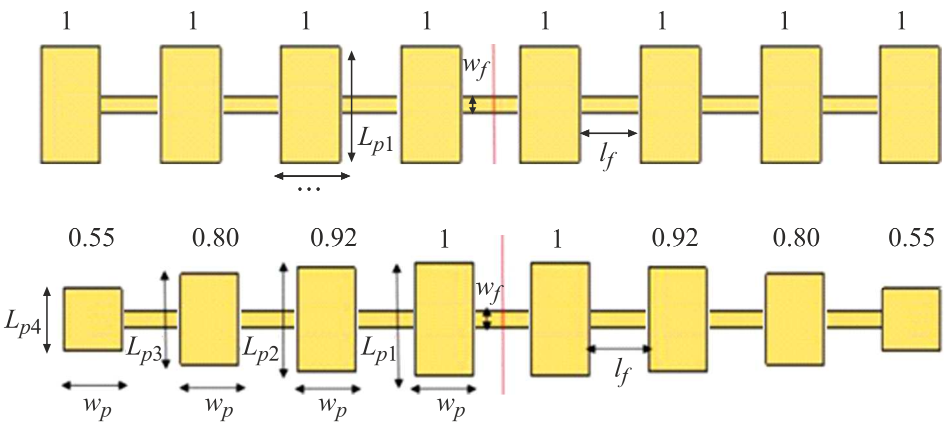

Figure 1. Uniform and modified linear antenna arrays.

ULAA and MLAA characteristics

Parameter	Examined antenna type			
	ULAA		MLAA	
Relative operating band with SWR < 2.0	SWR exceeds 2		11 %	
Boundary frequencies for parameter determination, GHz	24	26	24	26
Maximum achieved gain at the indicated frequency, dBi	12.154	8.160	13.22	13.165
Side-lobe radiation level at the indicated frequency, dBi	−10.6	−9.25	−11.25	−8.96
Antenna efficiency at the indicated frequency	92.0	88.7	91.6	91.8
Main-lobe beamwidth at the level of −3 dB, deg	11.77	12.42	13.33	10.2

The designs of a uniform linear antenna array (ULAA) and a modified linear antenna array (MLAA) are shown in Fig. 1.

The Roger RT5880 material with a relative permittivity of 2.2 and loss tangent $\operatorname{tg}\delta = 0.0009$ was used to construct these antennas; the substrate thickness is $h = 0.8$ mm.

The geometric dimensions of the radiators and the feed line width were optimized, and the influence of shape of a non-uniform feed line on antenna matching within the operating frequency range was investigated. Modeling was performed using the specialized Altair FEKO program based on the rigorous full-wave method of moments.

Figure 2 presents the frequency response of the reflection coefficient for the ULAA and MLAA models with a non-uniform feed line with its width varying exponentially. It can be seen that a standing wave ratio (SWR) < 2 may be achieved within the frequency range of 21.1−26.25 GHz by adjusting the radiator dimensions in accordance with the Chebyshev polynomials, while the ULAA retains SWR > 2 at frequencies up to 27.5 GHz. The characteristics of the

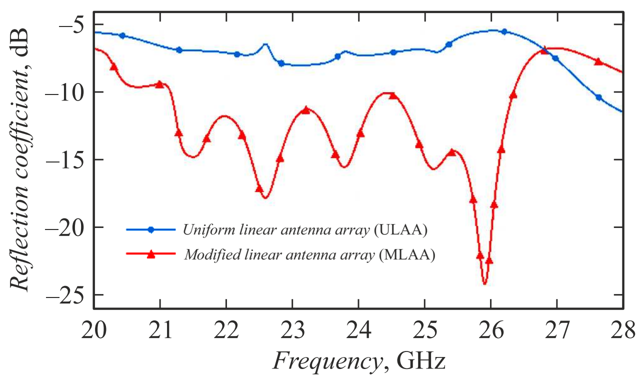

Figure 2. Frequency response of the reflection coefficient of ULAA and MLAA designs.

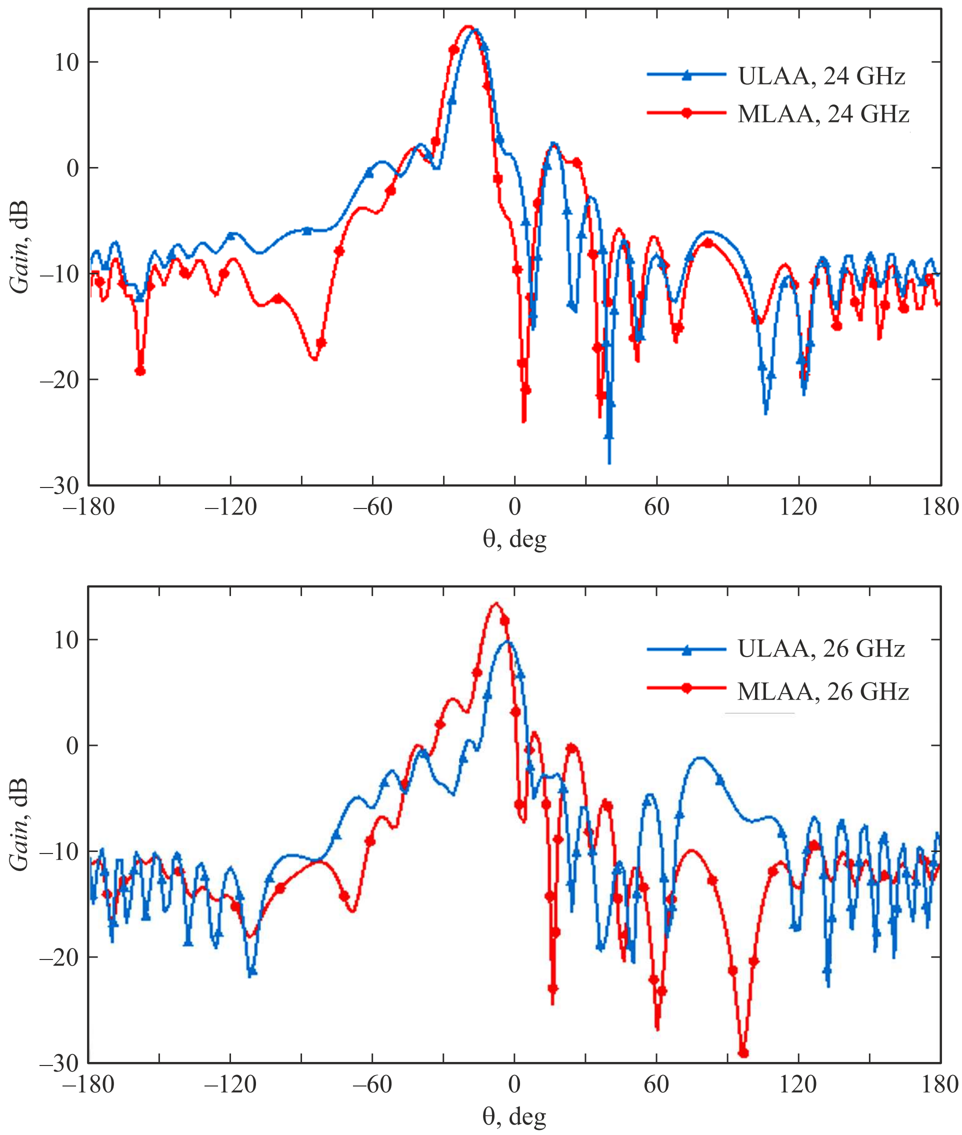

Figure 3. ULAA and MLAA radiation patterns at fixed frequencies.

ULAA and MLAA designs at fixed frequencies of 24 and 26 GHz are compared in the table.

It follows from the ULAA and MLAA radiation patterns shown in Fig. 3 at two fixed frequencies in the E-plane that the MLAA design provides a higher gain than ULAA.

The examination of influence of the substrate thickness on the frequency response of the reflection coefficient of the modified antenna (Fig. 4) revealed that a reduction in thickness leads to deterioration of the frequency properties of the MLAA design; in addition, the electrical strength of the antenna decreases.

As the substrate thickness increases, the reflection coefficient increases throughout the entire range under study, but the frequency response of the reflection coefficient becomes smoother. It is not advisable to increase the substrate thickness if the propagation of surface waves is to be limited. One way to reduce the influence of surface waves is to use multilayer substrates without increasing the overall thickness or to use metamaterials as part of the substrate.

Thus, the design of a linear Dolph–Chebyshev antenna array operating within the 24–26.5 GHz frequency range with a non-uniform feed line, which has an exponentially varying width, was examined, and the geometric parameters were optimized using Altair FEKO. Compared to the ULAA design, MLAA provides higher gain and a low sidelobe level. The antenna characteristics are sensitive to the thickness of the substrate, which should be chosen so as to balance the electrical strength of the antenna against the desired threshold of influence of surface waves on the characteristics.

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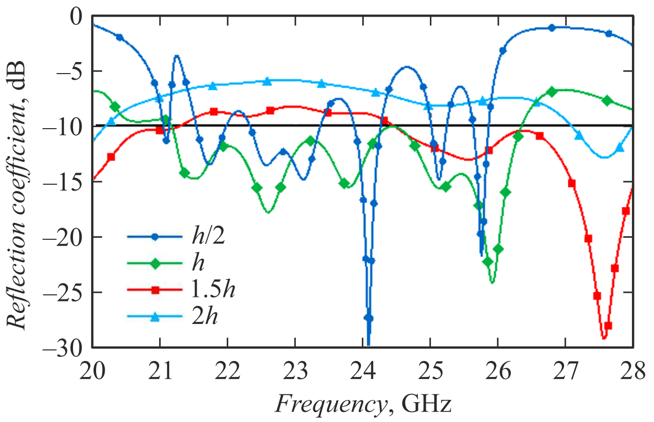

Figure 4. Frequency dependences of the reflection coefficient for different thicknesses of the MLAA substrate, $h = 0.7874$ mm.

29-00970/) and was performed at the Southern Federal University.

Conflict of interest

The author declares that she has no conflict of interest.

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