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A printed VICTS antenna array with wide-angle mechanoelectrical scanning

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A printed VICTS antenna array with wide-angle mechanoelectrical scanning has been developed. A design of a printed antenna array with a thickness of less than 6.5 mm is proposed, providing wide-angle mechanoelectrical scanning in the Ku-band. A full-wave electromagnetic analysis of the proposed antenna array was carried out. Radiation patterns were obtained for different rotation angles of the radiating layer relative to the feeding layer, and the specific features of mechanoelectrical scanning were investigated. It is shown that the developed printed VICTS antenna array provides scanning over more than 75° from the normal to its plane. Such an array can be used in satellite communications-on-the-move terminals where a low profile and wide-angle scanning are required, especially in non-geostationary satellite systems.

Keywords: antenna array, VICTS, scanning antenna, printed antenna, SIW technology, satellite communications.

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The development of non-geostationary satellite groupings in Low and Medium Earth Orbits (LEO/MEO) is one of the key directions of the modern telecommunications industry [1–3]. Such systems are capable of providing broadband access to information services anywhere in the world, including hard-to-reach areas devoid of ground infrastructure [4]. Ground terminals for non-geostationary satellite networks require antenna systems with wide-angle beam scanning for continuous tracking of fast-moving satellites [5–7]. Among the existing approaches to the construction of scanning antennas for satellite terminals, three main directions can be distinguished. Phased array antennas perform fast electronic scanning, but are characterized by high cost and low availability of components, especially in the Ku and Ka-ranges [8,9]. Antenna systems with mechanical scanning based on mirrored antennas or antenna arrays with pivoting devices are a simpler solution from the point of view of antenna development, but they have large dimensions and weight, and, consequently, limited scanning speed [10]. The third approach to the construction of scanning antennas is antenna systems with mechanoelectric scanning. One of the possible options for implementing such a beam control method is the VICTS (Variable Inclination Continuous Transverse Stubs) technology proposed by Millroy in 2005 [11], which implements mechanoelectric scanning without using active microwave devices by rotating the radiating and feeder layers of the antenna. This approach allows combining a low profile design with a wide scanning sector in the angular plane at a moderate cost [12].

The VICTS antenna consists of two rotating discs. There is a row of extended slit radiators in the upper disk. In the lower (feeder) disk there is a waveguide beam-

forming network (BFN) on binary power dividers in the *H*-plane, which forms a quasi-TEM wave at the output of the divider to excite the emitters located in the upper disk of the antenna. The antenna is made by milling from aluminum. As the results of computational and experimental studies have shown, an all-metal VICTS Ku-band antenna with adiameter of 500 mm provides a beam scanning sector of more than 60° relative to normal with moderate gain degradation, while the antenna profile height was about 40 mm [13]. At the same time, the all-metal implementation has a number of significant limitations: significant labor intensity and cost of machining complex elements (decelerating structure, waveguide power divider), significant weight of the structure, strict manufacturing tolerance requirements and scaling complexity for mass production.

In this paper, we propose an alternative approach to the implementation of a VICTS type antenna array based on printed circuit board manufacturing technology. This approach makes it possible to significantly reduce the antenna profile, reduce the cost of implementation, ensure high reproducibility of parameters due to standard technological processes, and also opens up opportunities for integrating the antenna with other functional components of the receiving path (filters, low-noise amplifier, etc.) [14,15]. At the same time, the transition to printed versions is fraught with a number of difficulties: additional losses in the dielectric material of the substrates, limitations of the technology of manufacturing printed circuit boards.

The purpose of this work is to develop and study a printed antenna array of the VICTS type with wide-angle mechanoelectric scanning.

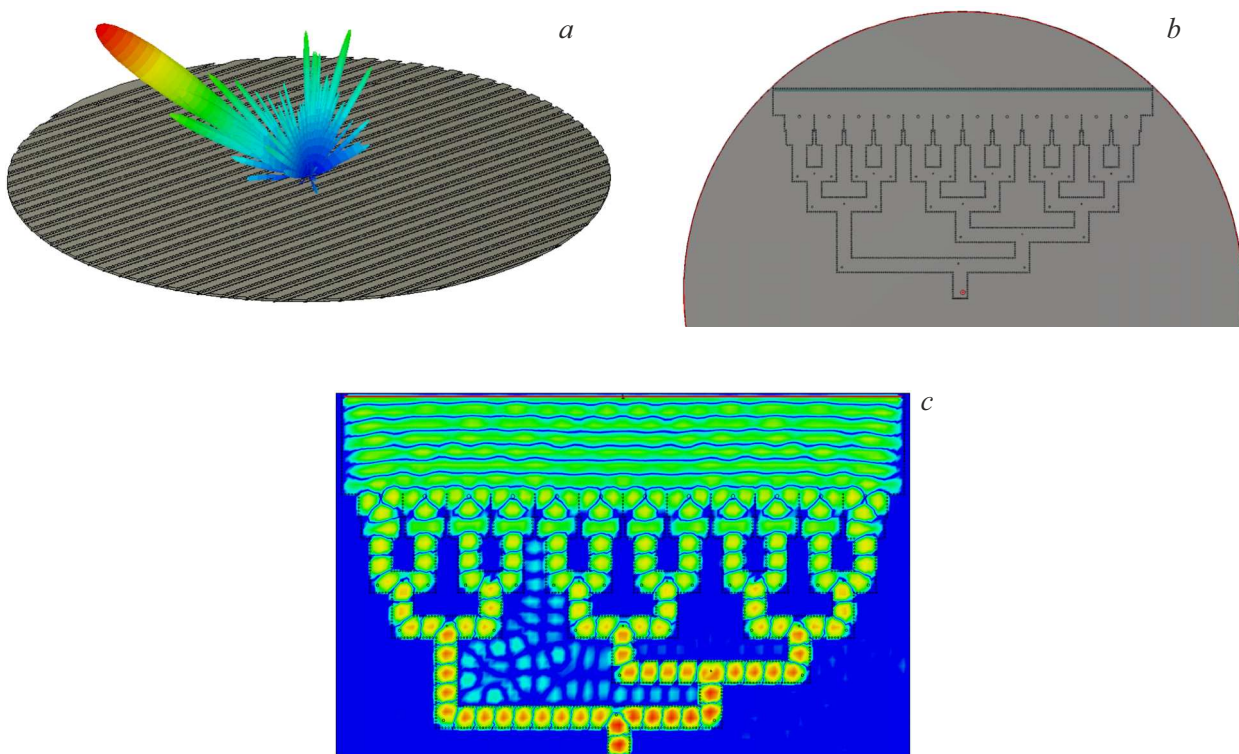


Figure 1. The antenna system. *a* — appearance of the antenna system with a directional pattern, *b* — BFN, *c* — field distribution in BFN.

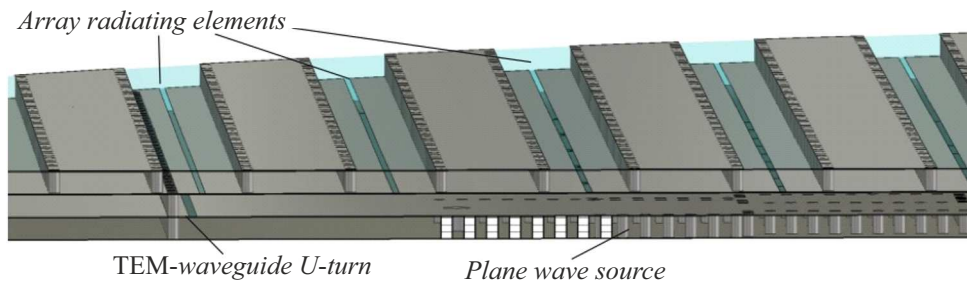


Figure 2. Structure of the antenna array.

As with the all-metal implementation, the VICTS printed antenna consists of two disks: an upper radiating and a lower feeder (Fig. 1, *a*). Scanning in the angular plane is performed by rotating the upper disk relative to the lower — plane wave source. The azimuth scanning is performed by synchronous rotation of two discs. A material based on fluoroplast — Rogers 5880 with a thickness of 2 mm with a relative permittivity of $\epsilon = 2.2$, a small tangent of the dielectric loss angle ($\tan \delta = 0.0009$) and a roughness of copper foil ($R_a = 0.3 \mu\text{m}$) was selected to implement the VICTS printed antenna as a dielectric substrate, which ensures low losses and a low coefficient of friction between the disks. The antenna diameter was 500 mm.

A BFN is located in the lower disk of the antenna, which forms a quasi-DARK wave for exciting slot radiators in the upper disk of the antenna. The plane wave source is

implemented on the basis of binary power dividers made using the substrate integrated waveguide (SIW) (Fig. 1, *b*). The source consists of 12 stepped horns with an aperture divider in the opening. The length of the source was 340 mm. Unequal amplitude power dividers were used to form a uniform amplitude-phase distribution of the field. Since the power is supplied to a part of the emitters of a plane wave source through three binary dividers, and to a part — through four, special attention is paid to the phasing of the emitters. The phase difference between the emitters in the operating frequency band does not exceed 5° . The field distribution in the divider is shown in Fig. 1, *c*.

To reliably shield SIW waveguides and prevent parasitic connections between adjacent divider channels, it is necessary to correctly select the diameter of the metallized holes (d) — 1 mm — and the step between them (p), the step

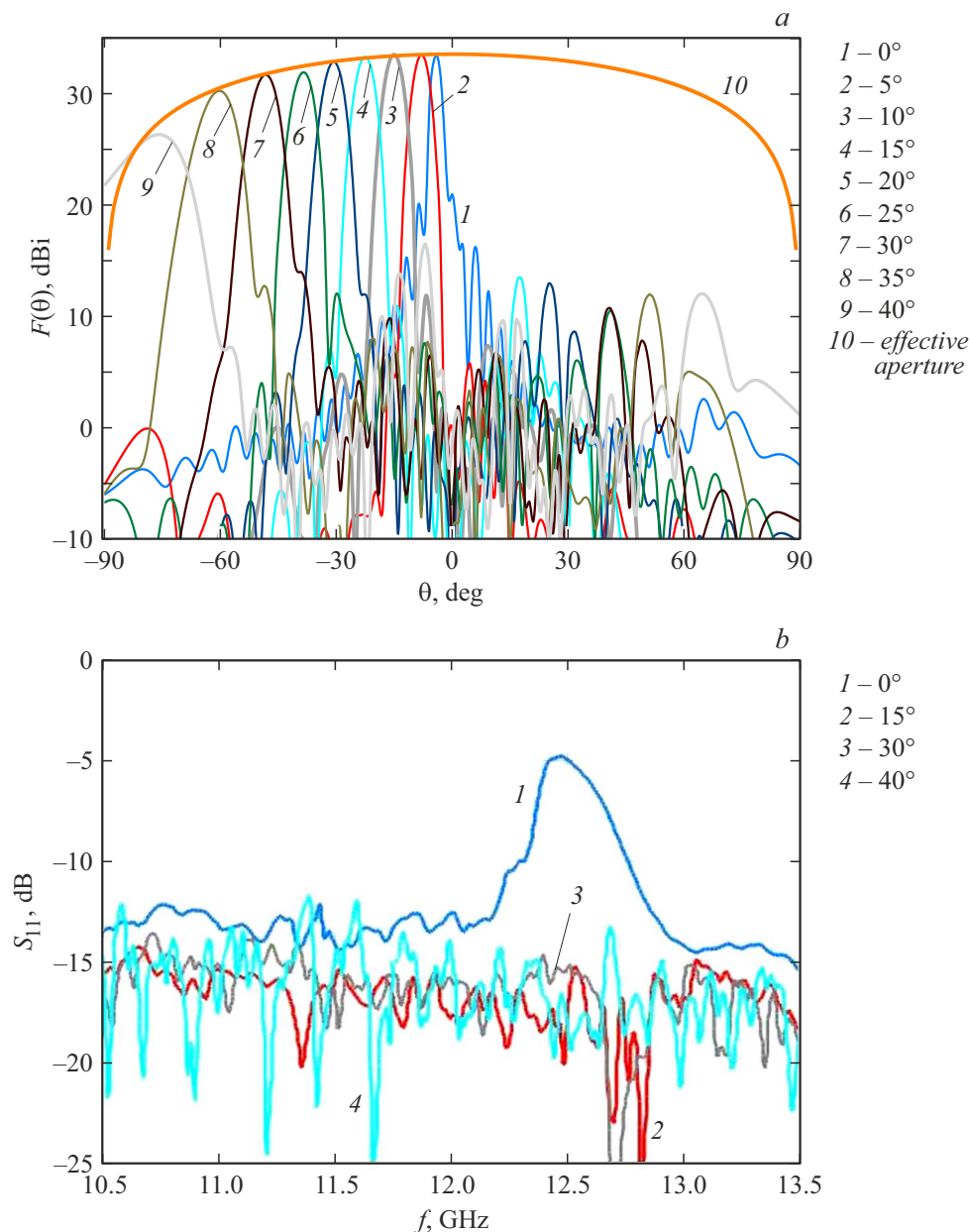


Figure 3. Calculated characteristics. *a* — cross-sections of radiation patterns in the angular plane at different angles of rotation of a disk with radiators at a frequency of 12 GHz; *b* — frequency dependences of the reflection coefficient at different angles of rotation of a disk with radiators; *c* — frequency dependences of the directional coefficient at different angles of rotation of the disc with radiators. The color version of the drawing is presented in the electronic version of the article.

varies from 2 to 3.5 mm depending on the location. To ensure the operation of the antenna in a wide frequency band, matching inhomogeneities in the form of metallized holes inside the dividers are introduced into the structure of the dividers.

The connection of the layer with the BFN and the layer with the radiators is carried out using a slit junction (Fig. 2). The reflection coefficient of such a transition does not exceed -20 dB in the frequency band 50%. A number of metallized holes may not touch the metallization on the side of the radiators, which is necessary to rotate one disk

relative to the other. A gap of 0.2 mm ensures leakage of the exciting oscillation power in an undesirable direction at the level of 0.2 dB.

The radiating layer of the antenna is made in the form of stepped horns (Fig. 2), the side walls of which are formed using metallized holes. The widths of the coupling slits increase as you move away from the plane wave source to obtain an amplitude distribution that is close to uniform.

Numerical studies of the antenna array under consideration were carried out using the finite element method in the time domain. Fig. 3, *a* shows the cross sections of

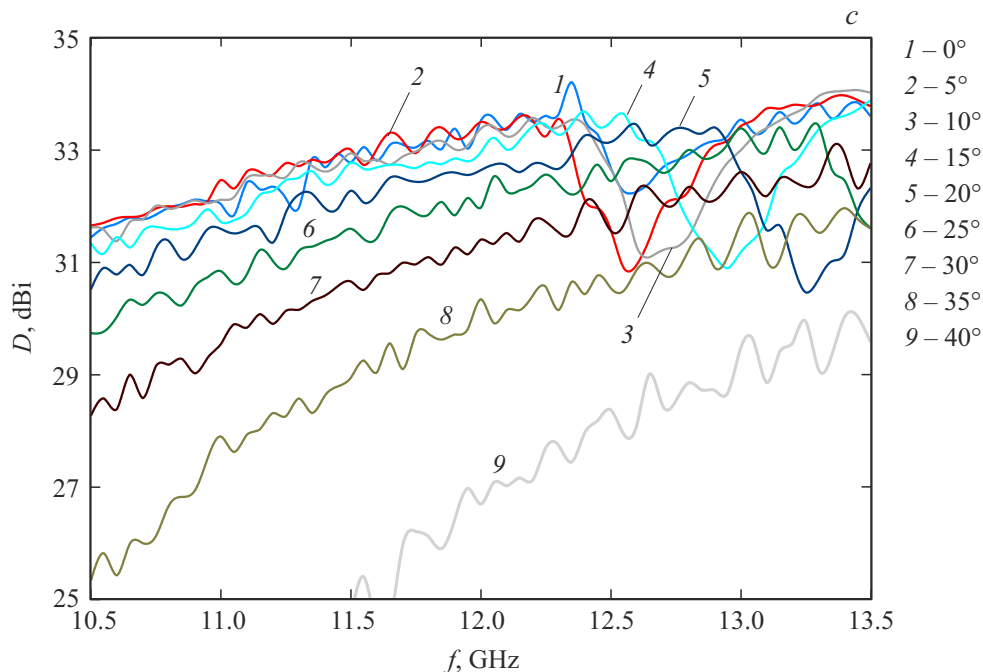


Fig. 3 (Contd.).

the radiation patterns of the studied antenna array in the elevation plane at the rotation angles of a disk with a plane wave source from 0 to 40° at a frequency of 12 GHz. It should be noted that when the disk is rotated from the BFN, scanning occurs not only in the angular plane, but also in the azimuthal plane, which is caused by a change in the effective grid pitch. To construct a family of directional diagrams, a maximum cross section was found for each of the rotation angles of the disk with the source. The decrease in directivity correlates well with a decrease in the effective aperture of the antenna (the curve *effective aperture* in Fig. 3, *a* corresponds to a surface utilization factor of 60%) up to the beam deflection at 80°. The worst value of the reflection coefficient –5 dB at the upper frequency of the operating range (Fig. 3, *b*) is observed when the source is located strictly parallel to the radiators, in this case the reflected signal from the radiators returns to the source in phase. When the source is rotated relative to the radiators, the reflection coefficient improves to the level of –15 dB and the characteristic becomes linear over the entire operating frequency band.

The antenna has frequency scanning due to the sequential power supply of the grid emitters. The beam can be directed perpendicular to the antenna array at only one frequency. This leads to the appearance of a blind spot in the operating frequency range normal to the antenna, where the beam cannot be directed under any combination of positions of the antenna discs. The antenna demonstrates a monotonous increase in the directional coefficient (Fig. 3, *c*) in the frequency range 10.5–12.3 GHz, at a frequency of 12.5 GHz, the antenna array beam passes through „zero“ (perpendicular to the antenna plane) and a decrease in the

directional coefficient is observed as well as a deterioration in the reflection coefficient characteristic of antenna arrays with serial power supply. The size of the blind spot can serve as a criterion for the operating frequency range of the developed VICTS antenna. For the blind spot $\pm 5^\circ$, the operating frequency range is 12–12.5 GHz ($\sim 4\%$), for 10° — 11.35–12.5 GHz ($\sim 10\%$). If the directional coefficient is allowed to degrade near zero deviation by 2 dB (12.5 GHz), then the operating frequency band can be doubled.

The directional coefficient of the printed version of the antenna array is comparable to that of the all-metal implementation. However, in the case of the printed version, the estimated losses are 1 dB, which is 0.7 dB more than in the case of the hollow version. The losses slightly increased in the rest of the grid (by no more than 0.3 dB). Using a plane wave source based on a parabolic reflector integrated into the substrate will reduce losses in BFN by 0.5 dB, however, the aperture utilization factor of the antenna surface will be reduced due to the decreasing amplitude distribution.

The proposed printed VICTS antenna allows for wide-angle mechanoelectric scanning. The advantage of the proposed solution is the low cost of execution due to the absence of active microwave elements. The scanning speed of the presented antenna system is potentially higher than in the case of using a purely mechanical method. This is due to the fact that the antenna under consideration rotates balanced disks around its axis, rather than the two-axis rotation of the entire antenna system.

According to the set of characteristics, the VICTS printed antenna concept is well suited for use in satellite communication systems based on non-geostationary satellites with a

scanning sector $\pm 60^\circ$ relative to the zenith, as well as for location tasks.

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Conflict of interest

The authors declare that they have no conflict of interest.

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