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Phased array beamforming networks

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The work is devoted to studying multibeam phased array beamforming networks based on the Butler matrix and Rotman lens. The study was performed under conditions similar to those in the telecommunication satellite service area. The microstrip circuit pattern was developed; the amplitude and phase frequency responses were investigated taking into account losses in materials. Array directional patterns for beamforming variants were calculated. Evaluation of adjacent ray overlay within the service area was carried out. Conclusions about acceptability of the proposed beamforming networks were made.

Keywords: beamforming network, antenna array, Butler matrix, Rotman lens.

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The general tendency to decreasing dimensions of telecommunication satellites [1] implies the necessity of more intense utilization of their surfaces. At the same time, for the purpose of reducing the weight and overall dimensions, several ordinary antennas of the same frequency range may be replaced with one multibeam phased array (PA) of antennas. The multibeam PA involves a beamforming network (BFN) that may be constructed based on different structures [2,3]. This paper considers BFNs based on the Butler matrix and Rotman lens. The study was performed at the preset values of the PA angular coverage area parameters and number of beams, with a restricted aperture size. For instance, there was considered a case with eight fixed beams within the satellite service area (with, if possible, a more uniform angular–range coverage with respect to the gain factor). Thus, the goal of this study was creating a multibeam PA under unified requirements but using different approaches to BFN construction.

As a single BFN element in which the minimum number of radiators per PA row was ensured due to uniform amplitude distribution, the four–beam Butler matrix was taken [4]. Such a BFN consists of functional modules realizing the power division with the quadrature phase shift, two overlays of planar transmission lines, and two 45° phase shifters. The Butler matrices may be implemented in the form of either a single–layer or double–layer microstrip circuit pattern. For instance, power dividers may be implemented in the form of microstrip quadrature directional couplers; the transmission–line overlays may be realized as two directional couplers connected in series; phase shifters may be formed as transmission–line sections.

A complete Butler–matrix BFN of the considered type for scanning in two planes has eight input and eight output ports. Two elements of the 4×4 Butler matrix are made in separate substrate layers according to the microstrip technology. The elements are combined in a single printed board with a screen in the intermediate metallization layer. Connection of the 4×4 matrices for orthogonal–plane scanning is realized via an element with bridge quadrature dividers mounted on one of the substrate external sides by using interlayer transitions through a plated hole (Fig. 1). If a material with dielectric permittivity $\varepsilon = 3.55$, thickness of 0.8 mm and feedline wave impedance of 50 Ω is used, the Butler matrix size is 120×200 mm at the design frequency of 2 GHz.

Another option for solving the problem of constructing BFN for a multibeam PA is the Rotman lens [5]. The Rotman lens advantage in this application consists in that, at the stage of design, the input/output phase relationships are not strictly fixed, and the number of inputs and outputs of BFN elements may be unequal and are to be properly selected.

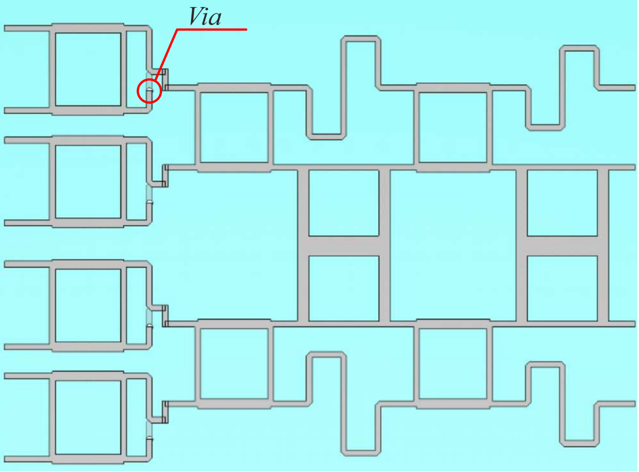

Figure 1. Dual Butler matrix with eight input ports (left) and eight output ports in two substrate layers (four ports per layer) (right).

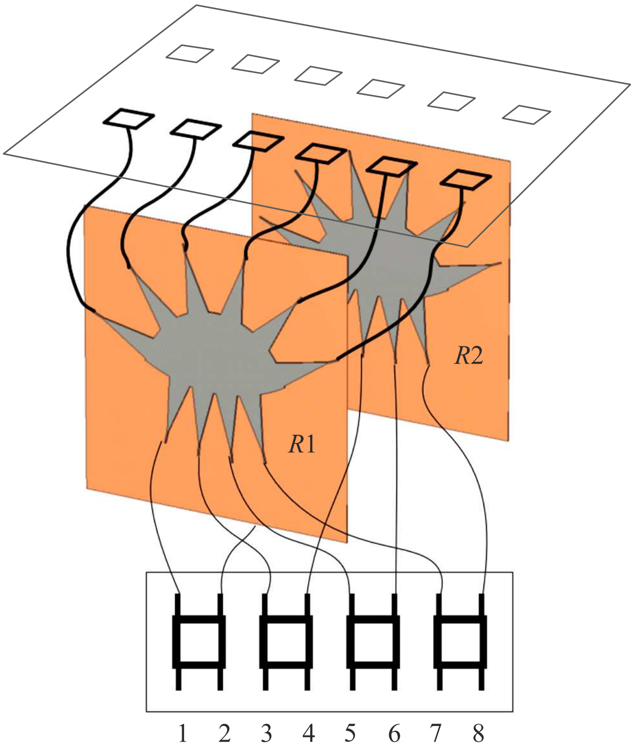

Figure 2. Illustration to the construction of a multibeam PA based on the Rotman–lens BFN.

The presented variant is based on a microstrip structure, i.e., a structure with a single solid–metal layer. In this case, the pattern is located on a dielectric material with $\varepsilon = 10$, the substrate size being 220 × 220 mm at the design frequency of 2 GHz. It is proposed to use two elements with printed Rotman lenses themselves having four inputs each and one element with bridge quadrature dividers. All the elements are combined in one printed board similarly to the above–described Butler–matrix BFN. Fig. 2 presents the structural diagram of PA with BFN. For more clearance, elements with Rotman lenses are drawn separately and designated as $R1$ and $R2$.

The decreasing character of the amplitude distribution in a Rotman–lens BFN, as well as the necessity to maintain high BFN efficiency, made it necessary to increase the number of radiators relative to that in the Butler–matrix BFN. The study showed that the minimal radiatorsńumber per row sufficient to ensure PA characteristics similar to those of the above–described Butler–matrix BFN appeared to be six. In addition, to maximize the efficiency, the lens size was minimized, and a model free of typically present ballast ports was constructed [6,7].

To calculate the directional patterns (DP) for PA with the proposed BFN variants, the following models were used:
— electrodynamic models of the Butler matrix and Rotman lens accounting for losses in the dielectric material;
— mathematical approximation of DP in the electrodynamic model of the wide–angle microstrip radiator accounting for losses (with the radiator efficiency of 90%).

Thus, PA DPs were calculated based on results of preliminary electrodynamic modeling of BFN elements and electrodynamic modeling of microstrip radiators.

For the Rotman lens, the number of radiators in each row is six, the number for the Butler matrix is four. The distance between the radiators was selected so as to ensure their accomodation within a restricted aperture (150 × 300 mm) and appeared to be 0.5 of wavelength for PA based on the Butler–matrix BFN and 0.35 of wavelength for PA based on the Rotman–lens BFN.

In Fig. 3, the closed curves represent the levels of equal PA DP gain factors (GF) (7 to 10 dBi) from all eight inputs for PAs of the studied types. The large circle indicates the boundary of the satellite service area. Since it is necessary to obtain the most–uniform service area signal coverage,

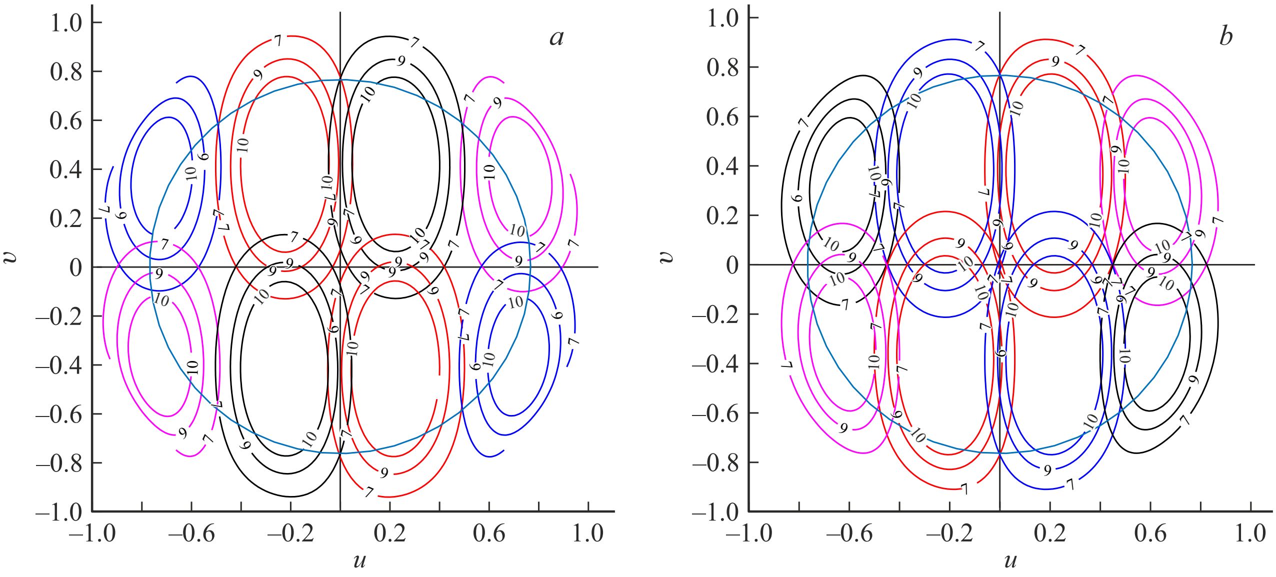

Figure 3. Directional patterns of 4 × 4 PA with Butler matrices (a) and Rotman lenses (b).

curves representing the maximum GF levels are redundant and not shown.

Comparison of DPs of two studied BFNs shows that the best uniformity of the angular sector coverage is ensured by the Rotman–lens BFNs. For instance, the minimal adjacent DP overlay takes place at GF of 7 dBi (as compared with the minimal DP overlay at GF of 4.8 dBi for the Butler–matrix PA).

This result can be achieved due to more flexible setting of the Rotman lens parameters; namely, by regulating the „input" ports positions it is possible to independently adjust the DP deviation angle for the relevant port. However, due to the quasi–optical operating principle of such a BFN even on a substrate with much higher dielectric permittivity, the Rotman–lens BFN has larger sizes. What should not be ignored is emergence of extra requirements for PA antenna elements since, due to restricted PA dimensions, each PA element should be smaller than half–wavelength, which is not always easily realizable.

The obtained results and their analysis allow us to speak about the possibility of achieving our goal, namely, creation of a multibeam PA in the framework of unified requirements but using different approaches. The revealed negative effects arising in operating the described BFN structures will promote the efforts of engineers and researchers in the direction of fulfilling the particular requirements.

Possibly, further studies will be devoted to considering the use in BFN a six-element Butler matrix [8] with connection of six radiators but with only four active inputs, which is expected to allow reduction of DP rays angular separation. As a hypothesis, the possibility of using for the same purpose bridge dividers with phase shift below 90° [9] in the 4×4 Butler matrix is suggested.

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Conflict of interests

The authors declare that they have no conflict of interests.

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