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Mathematical modelling of the spatial excitation system of a cylindrical active phased antenna array with electronic commutation

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This article discusses the excitation system of a cylindrical active phased antenna array with a spatial power supply system for the emitters. A brief historical comparison of the presented system with those based on the use of mechanical antenna rotation and a conformal phased antenna array with a matrix excitation system was performed. The advantages of an active phased antenna array with a spatial excitation system, its operational principles and the results of mathematical modelling are presented.

Keywords: emitter power supply system, active phased antenna array, directional pattern, all-round coverage, amplitude-phase distribution

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Introduction

It is known that conventionally used in radiolocation for all-round coverage are antenna systems with mechanical antenna rotation. This solution is fairly easily implemented technically, but is accompanied by a number of problems with respect to information processing, such as:

– limited target illumination time (i. e., time of antenna radiation pattern (RP) "contact" with the object of location), which increases demand for radar energy potential;

– impossibility to effectively combine the modes of detection and target designation with the target tracking mode;

– the problem of signal transmission from the rotating antenna to stationary signal processing equipment and indication devices has to be solved.

These and other factors impel the designers to give preference to conformal (spherical, circular, or cylindrical) phased antenna arrays (PAA).

The conformal (circular or cylindrical) PAAs have circular symmetry, hence they form beams whose width does not depend on the scanning angle. Due to this, the beam (RP) can be turned through 360°. However, obtaining a required amplitude-phase distribution across the aperture of such PAAs is associated with significant difficulties.

The researches undertaken in 1970–1990s were aimed at developing special matrix-type power supply systems [1, 2]. A matrix circuit of PAA power supply allows to transform amplitude-phase distribution (APD) of currents on the radiators (emitters) in such a way that it will be possible to control the beam by merely varying phases by means of phase shifters installed at the matrix circuit inputs [3]. Presence in such circuits of a distribution matrix with M inputs and M outputs, where $M < N$ (N – number of PAA radiators), requires application of M switches for N/M directions, as well as of a large quantity of connecting cables of equal electrical length.

An alternative to the matrix excitation system of conformal PAAs is a spatial excitation system with electronic commutation of radiators. As compared with the feeder power supply system of conformal PAAs, a spatial power supply system, in combination with active receive/transmit modules (APAA), has a wider bandpass and enables not only to create an RP with low side lobe level, but also to simultaneously generate a sum and difference RPs for monopulse processing of signals. The PAA design is considerably simplified too. These properties of a spatial power supply system of APAA make it a more attractive choice when designing new advanced radars and navigation systems with narrow-beam wide-angle scanning in azimuth and an RP of special shape (cosecθ type) in elevation.

Cylindrical APAA with spatial power supply system of radiators

Fig. 1 shows the design of a cylindrical APAA consisting of M pattern-forming circuits (PFC), each one of which contains a vertical power

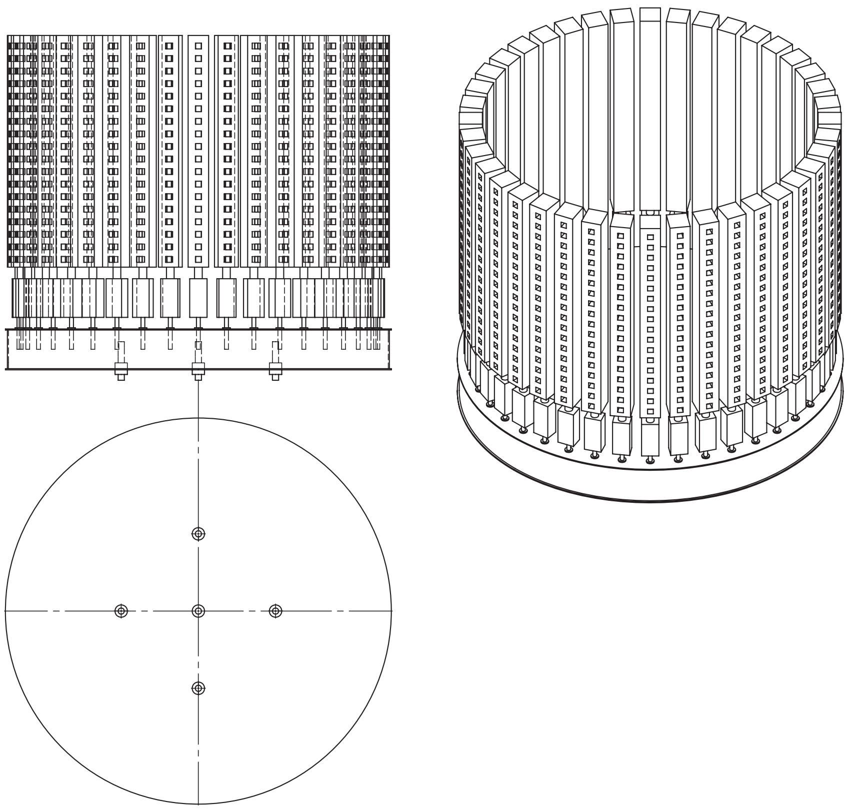


Fig. 1. Cylindrical APAA with spatial power supply system

divider connected to l radiators and forms in the vertical plane an RP of cosecant shape or sinθ/θ shape. Connected to the divider inputs are receive/transmit modules. Phase shifters of the receive/transmit modules provide PFC phasing in the horizontal plane for the purpose of forming a narrow RP in this plane. The number of APAA modules in the APAA is equal to the number of PFC, equalling to M.

For PFC power supply, a lens (Fig. 2) is used, which is essentially a radial transmission line formed by two circle-shaped plates. Distance l between the plates is less than 0.5λ, due to which conditions are created between them for propagation of electric field with vector $\vec{E}$, directed perpendicular to their planes. Excitation of the lens is provided by means of rods (see Fig. 2). The number of rods in Fig. 2 is 5. Rods 1–5 are located in the lens centre perpendicular to the plate's plane. Arranged along the lens perimeter with equal spacing are n' rods of the receiving array of the lens, acting as lens outputs.

Each one of the n' receiving rods of the lens is connected to APAA module by means of n' feeder line (if $n' = N$) or directly.

A diagram of amplitude distribution and phasing commutation (turn) circuit (CPC) is given in Fig. 3.

Beam scanning in space is provided through electronic turning of lens field amplitude distribution by means of the commutation and phasing circuit. Forming of APD displacement in the lens takes place through variation of excitation currents of the lens receiving rods synchronously with switching of the PFCs involved in the RP formation. Due to phasing of excitation currents of the central rods by means of two CPC phase shifters, beam displacement to angle $\Delta\alpha_p = 360°/M$ is provided.

The principle of electronic turning of the lens field amplitude distribution (Figs. 2 and 3) by two phase shifters is as follows. A signal from transmitter (TX) is distributed by two directions by means of a 6-dB directional coupler.

1. Signal

$$U_1 = \cos \omega_0 t, \quad (1)$$

whose relative amplitude is equal to unity, is supplied to central rod 1 and forms an omnidirectional component of the lens field amplitude distribution with constant phase in all directions.

2. Signal $U_{\text{отв}}$ with amplitude K is supplied to the difference input of sum-difference bridge 6, at whose outputs two signals are shaped:

$$U_{\text{B}_i} = 0.5K \cos(\omega_0 t + \pi/2) -$$
bridge upper arm,

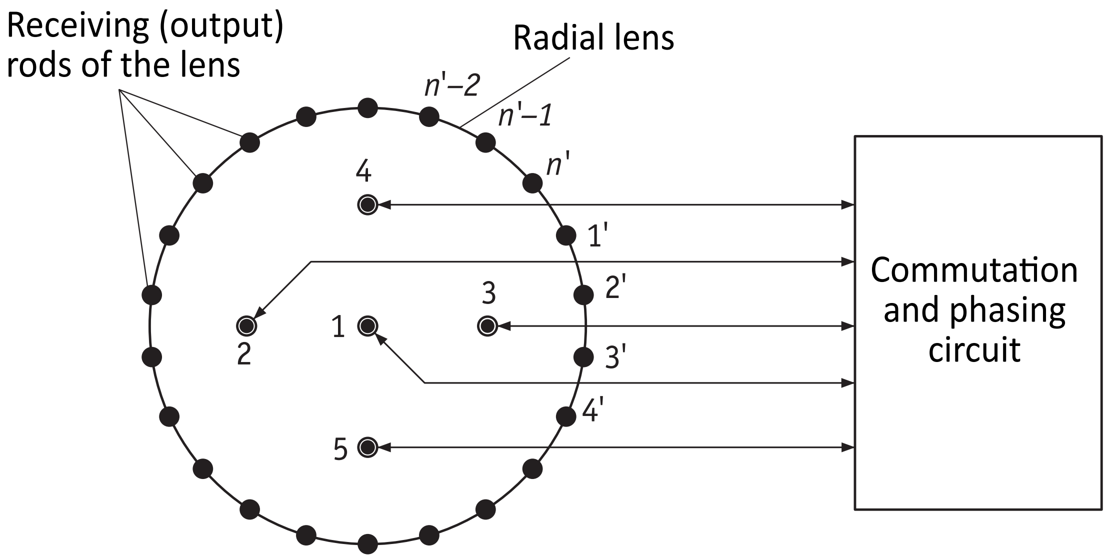


Fig. 2. HF switch of spatial power supply system of a cylindrical PAA

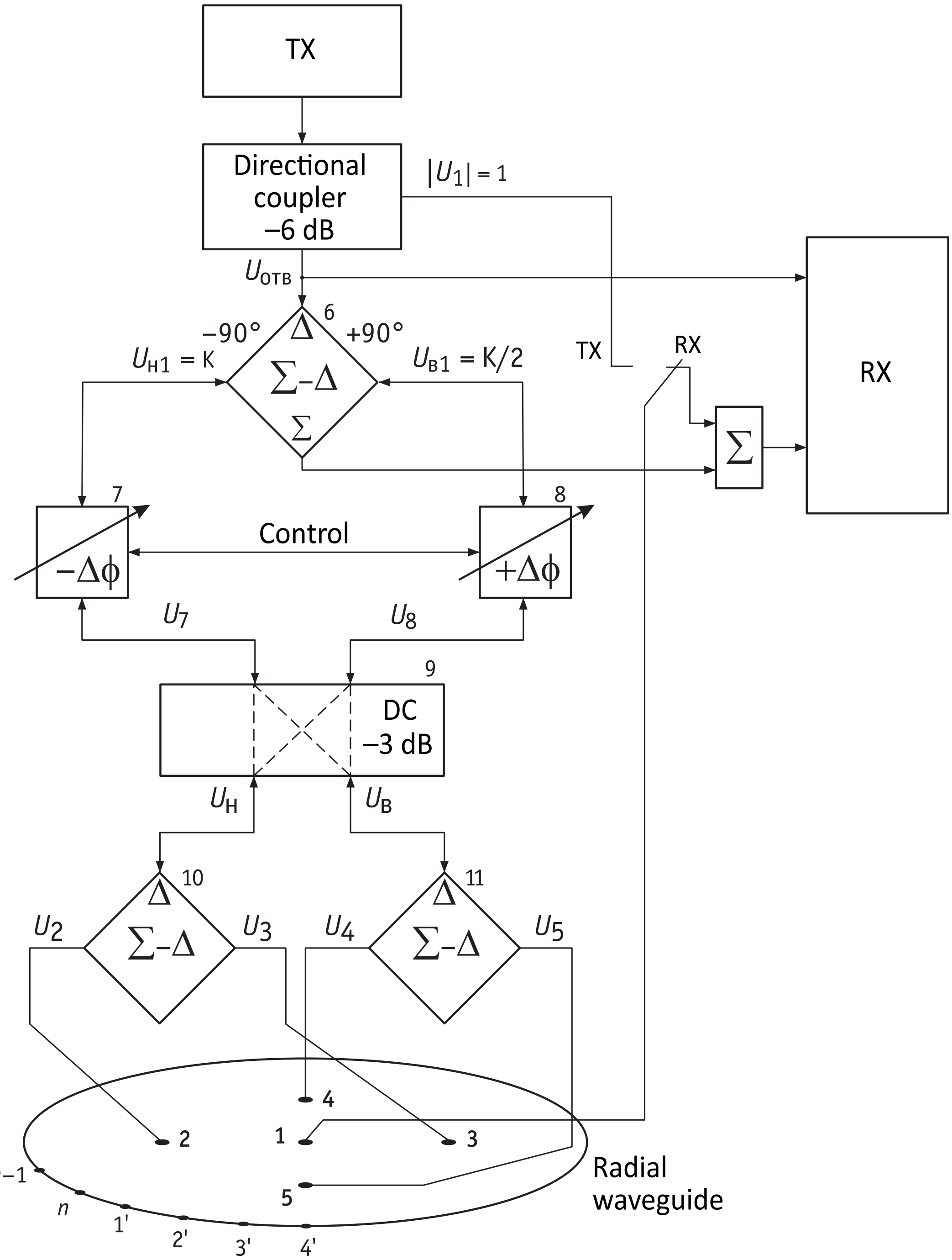


Fig. 3. Diagram of amplitude-phase distribution and phasing (CPC) turn:
1...5 – lens excitation rods; 1'...4'...*n*'–1, *n*' – lens receiving rods; DC – directional coupler;
Σ–Δ – sum-difference bridge; Δφ – controllable anti-phase phase shifters

$$U_{H_i} = 0.5K\cos(\omega_0 t - \pi/2) - \quad (2)$$

bridge lower arm.

Phase shifters 7 and 8 are included in the upper and lower arms of bridge 6. An operation mode of those phase shifters is selected such that the signal at the output of phase shifter 8 leads in phase, and at the output 7 lags in phase by a value of Δφ as compared with the input signal.

$$\begin{aligned} U_7 &= 0.5K\cos(\omega_0 t + \pi/2 + \Delta\varphi), \\ U_8 &= 0.5K\cos(\omega_0 t - \pi/2 - \Delta\varphi). \end{aligned} \quad (3)$$

Signals from phase shifter outputs are supplied via 3-dB coupler 9 to the difference input of sum-difference bridges 10, 11.

The signals look as follows:

$$U_H = k\cos(\Delta\varphi + \pi/4)\cos(\omega_0 t + \pi/4),$$
$$U_B = k\sin(\Delta\varphi + \pi/4)\cos(\omega_0 t + \pi/4). \quad (4)$$

Voltages U_2, U_3 and U_4, U_5 excite lens central rods: 2, 3 and 4, 5, respectively. In so doing, rods 2 and 3 (4 and 5) are excited in anti-phase. As a result, an APD is shaped, depending on direction (α), which at $d > \lambda$ (where d – distance between central rods of the lens) is associated with additional voltage phase on rods 2 and 3 by the relationship

$$\varphi_{2-3} = \pm\frac{\pi d}{\lambda}\sin\alpha, \text{ if } d \geq \lambda, \quad (5)$$

and for rods 4 and 5, by the relationship

$$\varphi_{4-5} = \pm\frac{\pi d}{\lambda}\cos\alpha, \text{ if } d \geq \lambda. \quad (6)$$

The APD in the lens is determined by the following formulas:

$$U_\Sigma = U_1 + [U_2(\Delta\varphi, \alpha) + U_3(\Delta\varphi, \alpha)] + [U_4(\Delta\varphi, \alpha) + U_5(\Delta\varphi, \alpha)], \quad (7)$$

where

$$U_2(\Delta\varphi, \alpha) + U_3(\Delta\varphi, \alpha)] = -\sin(\Delta\varphi + \varphi_{2-3}(\alpha) - \pi/4),$$
$$U_4(\Delta\varphi, \alpha) + U_5(\Delta\varphi, \alpha)] = -\sin(\Delta\varphi - \varphi_{2-3}(\alpha) - \pi/4) + \cos(\Delta\varphi - \varphi_{4-5}(\alpha)) \quad (8)$$

and $\varphi_{2-3}(\alpha)$, $\varphi_{4-5}(\alpha)$ are determined by formulas (5) and (6), respectively.

$U_1 = A_0\cos(\omega_0 t + \pi/4)$ – voltage on central rod 1.

The direction of APD curve maximum is determined by formulas (7) and (8).

In this way, variation of the value of Δφ from zero to 360° ensures synchronous turn of the lens APD through 360°. When receiving signals from aircraft from a direction forming angle α with the line connecting central rods 2 and 3, a sum signal and a difference signal are shaped at the output of sum-difference bridge 6 (see Fig. 3).

Modelling of arc APAA with spatial power supply system

A mathematical model of conformal APAA with a device for spatial (optical) excitation of radiators has been developed. The model serves to study RP characteristics of a cylindrical APAA excited by a lens (parallel-plate radial line) consisting of two parallel plates along the periphery of which $n' = M$ receiving rods are arranged (M – the number of receive/transmit modules and APAA PFCs).

Excitation of the lens was provided by means of the central rods, 5 or 9 pieces, arranged around the circumference with the diameter $d = \lambda$, where λ – wave length.

The use of 9 or 5 rods allows to form amplitude distribution ensuring different levels of side lobes in a cylindrical APAA RP. However, it required inclusion of four additional power dividers in the excitation circuit so as to provide distribution of power from the outputs of bridges 10 and 11 (Fig. 3) between eight central rods.

The peripheral rods of the lens are arranged equidistantly around the circumference with the diameter determined by the cylindrical APAA RP width in the azimuthal plane. The distance between PFCs is taken equal to 0.63λ.

The APAA active sector, which shapes the azimuthal RP, contains $N = M/l$ radiators (PFCs), where l = 3 or 4, and, on the one hand is determined by the RP width, while on the other hand is restricted by the requirement for the lens to shape such amplitude distribution that will ensure the minimum level of the RP side lobes and minimum of the power supplied to the modules outside of the APAA active sector. To study those properties, the model employed an APAA with lens excited by 5 (Fig. 3) and 9 (Fig. 4) rods.

Modelling was performed of an APAA with the number of radiators $M = 109$, with the active sector containing $N = 53$ modules arranged on an arc β = 120°. Aperture commutation was implemented with angular pitch $\Delta = \beta/N$, and angular position of the amplitude distribution maximum and, accordingly, of RP maximum position was determined by the expression

$$\theta_i = (c-1)\Delta - \frac{N-1}{2}\Delta + \Delta p,$$

where $i = 1, 2, \dots N$; $p = 1, 2, \dots$

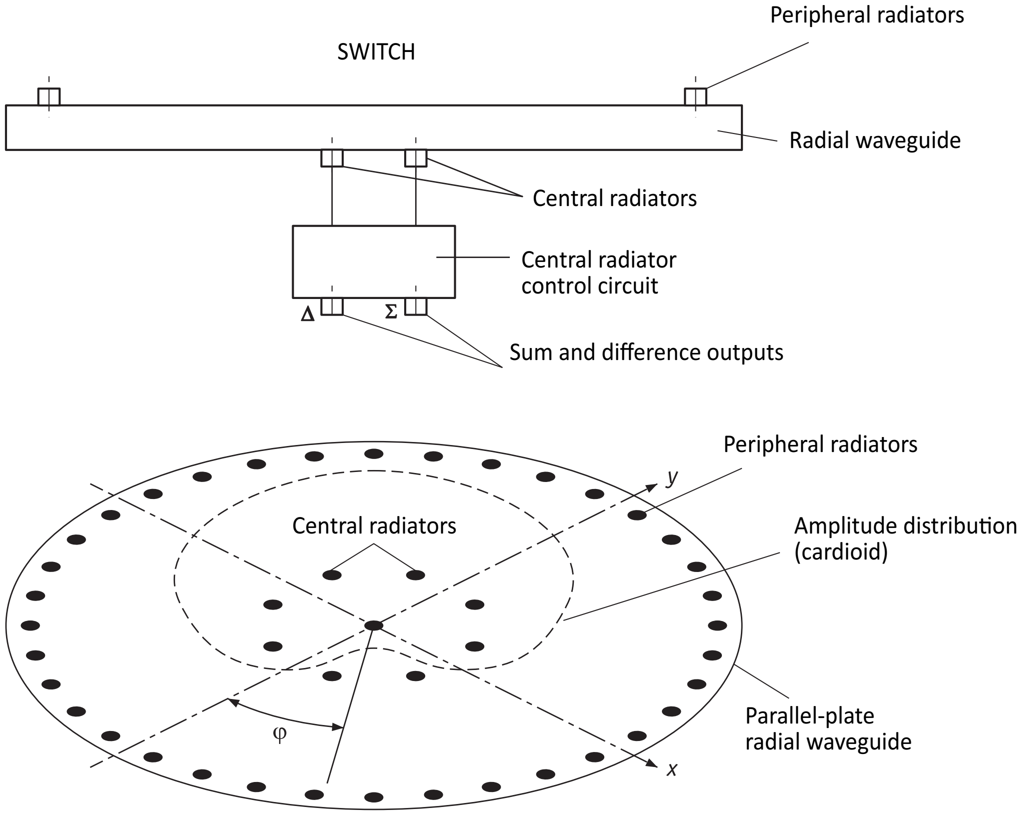


Fig. 4. Parallel-plate radial waveguide

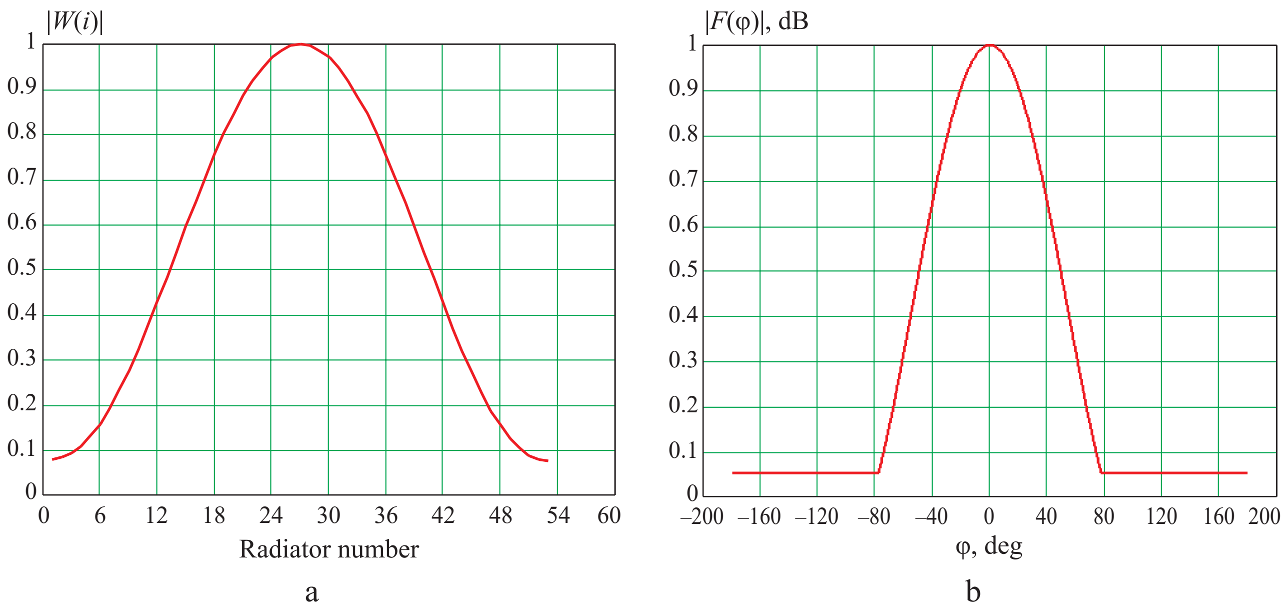


Fig. 5. APD: a – 9-rod lens; b – APAA radiator RP

Amplitude distribution for the 5-rod lens was calculated by formula (7), and for the 9-rod lens – by formula (11).

$$W[i]=1+k\sum_{t=1}^{8}\exp\left(\frac{2\pi}{\lambda}\left[x_t u(i,p)+y_t V(i,p)\right]\right), \quad (11)$$

where $i=\overline{1,N}$; $p = 0, 1, 2,...$

$$U(i,p)=\cos(\theta_i)-\cos(\Delta\cdot p),$$
$$U(i,p)=\sin(\theta_i)-\sin(\Delta\cdot p) \quad (12)$$

where $\{x_t, y_t\}$ – coordinates of the t-th rod in the coordinate system (Fig. 4). The APAA radiation pattern in the azimuthal plane was calculated

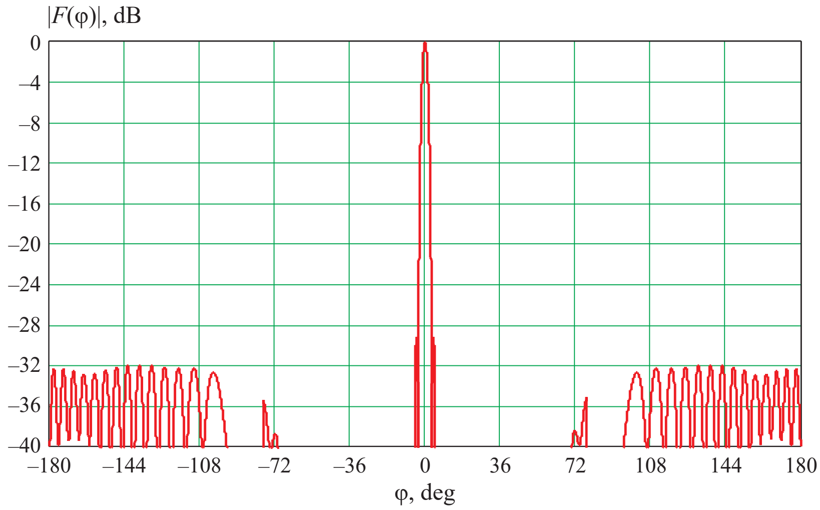


Fig. 6. RP of APAA (β = 120°) excited by a 9-rod lens

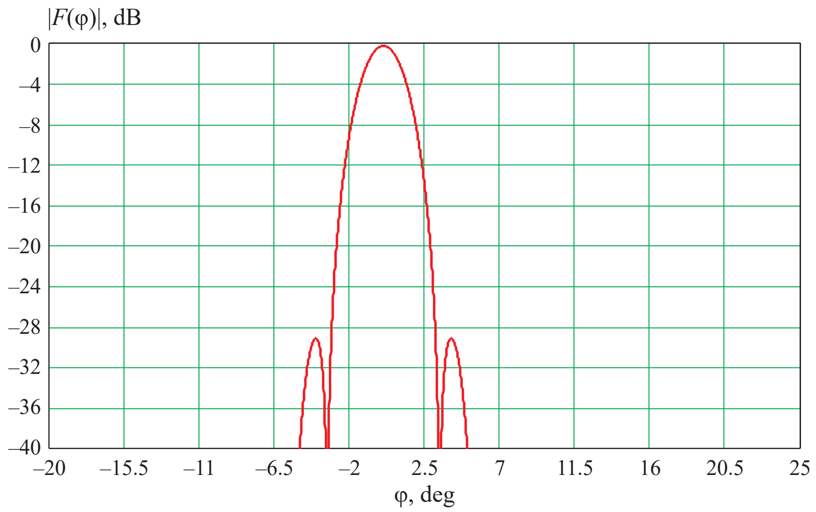


Fig. 7. RP of an arc APAA excited by a 9-rod lens

by the formula for a fixed active sector with the maximum in direction $\Delta \cdot p = \varphi_p$:

$$F(\varphi,\varphi_p) = \sum_{i=1}^{N} W[i] F_{\text{из}}(\varphi-\theta_i) e^{\frac{2\pi R}{\lambda}\left[\cos(\varphi-\theta_i) - \cos(\varphi_p-\theta_i)\right]}. \quad (13)$$

Fig. 5a shows amplitude distribution $W[i]$ formed by a lens excited by 9 central rods. Fig. 5b shows RP of APAA radiator. Shown in Figs. 6, 7 are RPs of APAA excited by a 9-rod lens.

Also modelled was an option of cylindrical APAA excitation by a radial lens containing 5 central rods, and APD of "cosine on a pedestal" type, formed by APAA active modules. It should be mentioned, too, that this APD was modified for arc PAAs according to the method described

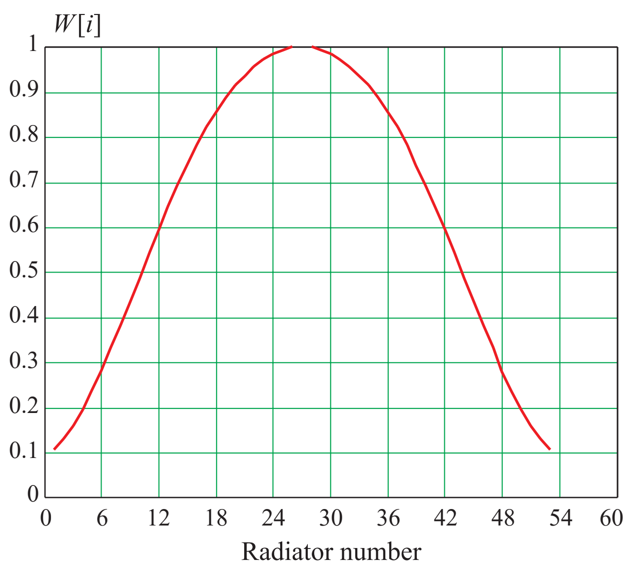
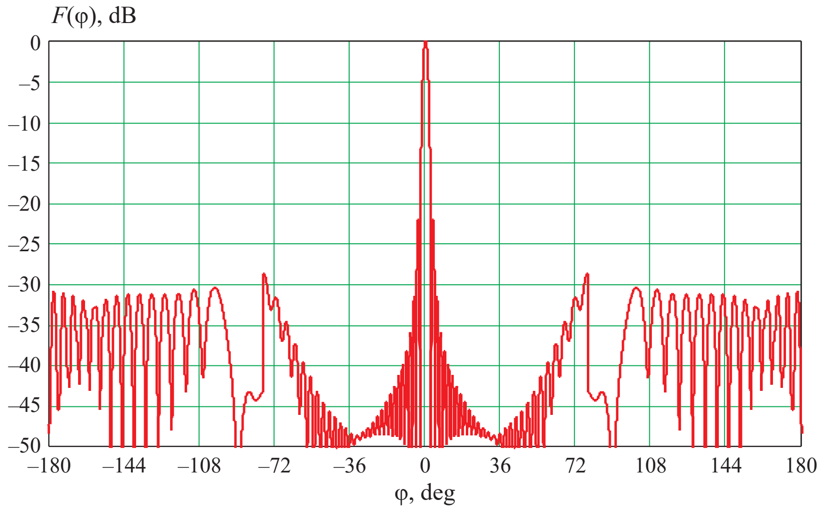
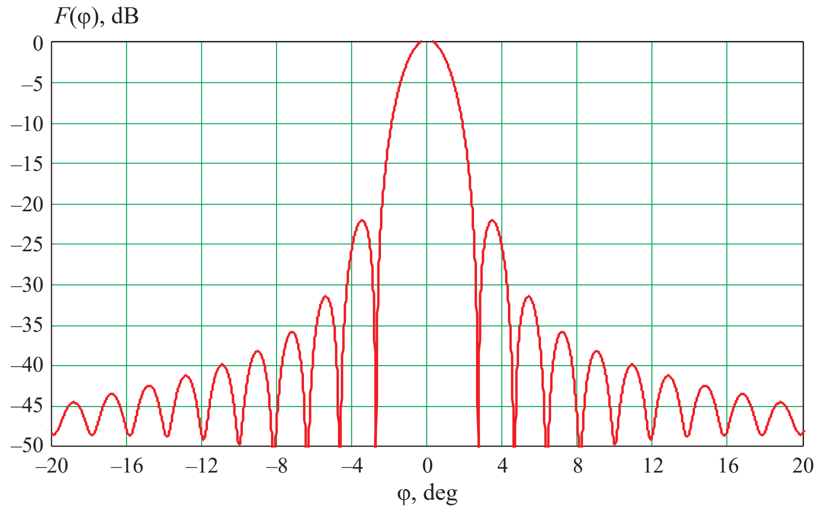


Fig. 8. APD created by a lens with 5 central radiators and $N = 53$ peripheral radiators



a



b

Fig. 9. RP of an arc APAA (β = 120°, N = 53) with APD created by a 5-rod lens

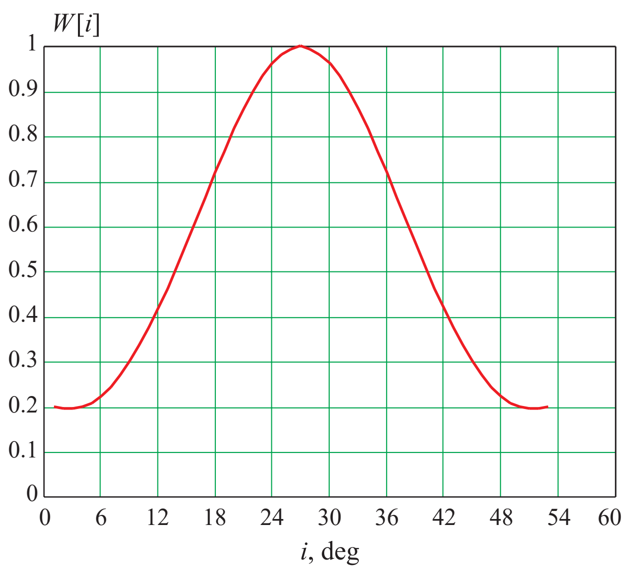


Fig. 10. Modernised APD of an arc APAA (β = 120°, N = 53)

in [4]. Figs. 8 and 9 show the APD of a 5-rod lens and RP of an arc APAA (β = 120°, N = 53). The level of RP side lobes was minus 23 dB. As a result of creating a Hamming amplitude-phase distribution, modified for arc PAAs, on the active modules and exciting APAA by a 5-rod lens (Fig. 10), the maximum side lobes level of the APAA RP became less than minus 25 dB (Figs. 11 and 12).

Conclusion

Application of the method of spatial (optical) excitation with electronic commutation of cylindrical APAA radiators makes it possible to form a narrow beam in the azimuthal plane and ensures electronic scanning within the 360° limits.

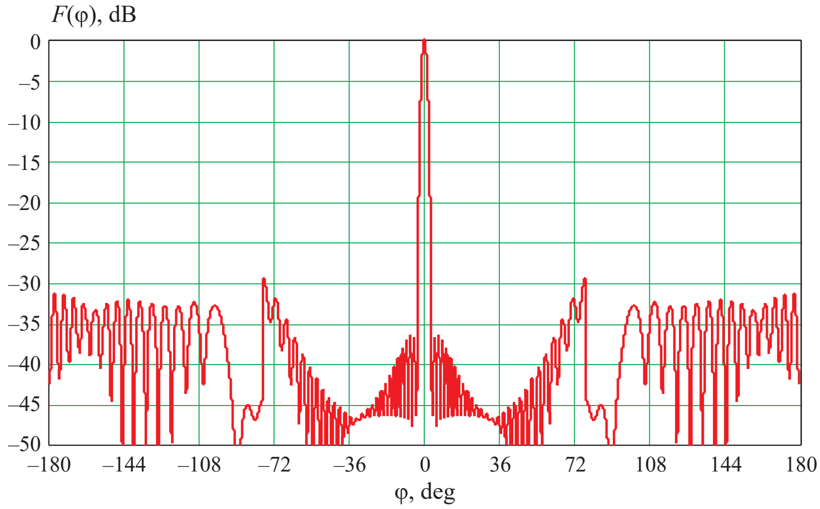


Fig. 11. RP of an arc APAA (β = 120°, N = 53) with modified Hamming APD, excited by a 5-rod lens

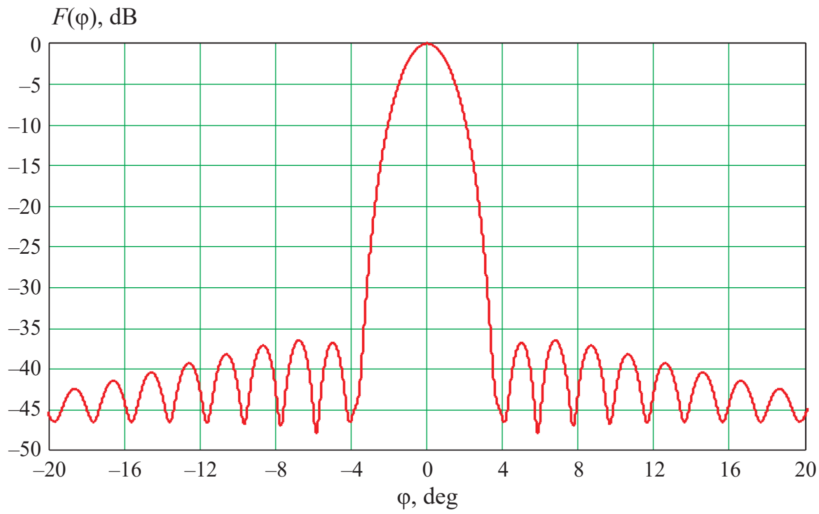


Fig. 12. RP of an arc APAA (β = 120°, N = 53) with modified Hamming APD, excited by a 5-rod lens

In that case, no branched feeder line and multi-position switches are required. Moreover, the considered scheme of APAA power supply enables to simultaneously form both sum and difference RPs for monopulse processing of signals. In so doing, the PAA circuit becomes considerably simpler (no crossover switches and signal adders of the left and right PAA aperture halves are required, etc.) as compared with feeder power supply systems using switchable matrix excitation circuits. Application of a radial transmitting (receiving) lens, consisting of two round plates with air or dielectric filling, makes it possible to create a small-size broadband excitation lens. Application of the considered circuits and APAA receive/transmit modules ensures the minimum excitation signal loss outside of the APAA active sector and allows to form a beam with low level of the side lobes, narrow in the azimuthal plane and broad (of special shape) in the elevation plane.

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Математическое моделирование пространственной системы возбуждения цилиндрической активной фазированной антенной решетки с электронной коммутацией

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В статье рассматривается система возбуждения цилиндрической активной фазированной антенной решетки с пространственной системой питания излучателей. Проведено краткое историческое сравнение с системами, основанными на применении механического вращения антенны и конформной фазированной антенной решетки с матричной системой возбуждения. Представлены преимущества использования активной фазированной антенной решетки с пространственной системой. Описаны принципы ее работы и представлены результаты математического моделирования, раскрывающие содержание преимущества активной фазированной антенной решетки с использованием пространственной системы возбуждения.

Ключевые слова: система питания излучателей, активная фазированная антенная решетка, диаграмма направленности, круговой обзор, амплитудно-фазовое распределение

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