The First Phased-Array Antennas in Russia: 1955-1960

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Abstract

The first phased-array antenna in the Soviet Union was developed under the supervision of Professor Yuri Yurov, at Leningrad Electrical Engineering Institute (Technical University), in 1955. It was a four-element array of dielectric-rod radiators, fed through reciprocal ferrite phase shifters. The array was intended for use in radar, for automatic aiming at the target. In Yurov's group, the theory of phased-array antennas was developed. In 1960, a 61-element array, in the form of a lens filled with ferrite phase shifters, was designed, manufactured, and investigated. Later, the investigations were moved from the university to industrial research centers.

Keywords: Phased arrays; phased array radar; ferrite phase shifters; lens antennas; dielectric antennas; history

1. At the Very Beginning

In the early fifties, we were students at the Radio Engineering School of Leningrad Electrical Engineering Institute[1]. During the summer semester of 1953, male students of the Radio Engineering School were mustered into practical military work, where, in particular we were shown radar, for automatically aiming at aircraft. That was a Soviet analog of the American SCR 584. The radar made a great impression on us, the future radio engineers. More than 40 years have now gone by. However, we clearly remember how a parabolic antenna followed the aircraft, and how we could watch in a small optical telescope, connected with the parabolic antenna, only a slight trembling of the silhouette of the aircraft around the cross in the telescope sight. The officer told us that the central element in the radar aiming system was a rotating radiator, which formed the scanning radiation pattern of the antenna. Returning to the School, we told Professor Yu. Yurov how impressed we were with the radar aircraft automatic-aiming system. The professor invited us to take part in a project that was directed at developing an antenna with a scanning radiation pattern, comprising no mechanically moving components. The immediate goal of the project was to increase the frequency of conical scanning, in order to improve the accuracy of the tracing.

Being included in the work on the project, we learned that the idea of controlling the position of the beam of a system of coherent emitters had been discussed many years[2]. The first antenna with a "non-mechanically" controlled radiation pattern did have phase shifters, in the form of mechanically controlled devices. Even the first radar-scanning antenna [1] was based on mechanically rotated phase shifters. The mechanical phase shifters could not provide the required speed of movement of the radiation pattern of the antenna. The development of automatic tracking set the task to provide controlling the antenna beam in short time intervals, first of the order of milliseconds, and then of the order of microseconds, or even of part of a microsecond. Thus, the problem of developing the electronically scanned antenna was formulated.

Prof. Yurov suggested designing phase shifters based on a waveguide partially filled with ferrite. The electrodynamic properties of the ferrite inset could be controlled by an external magnetic field, which was generated by a current driven by an electronic unit. During the period of 1954-1955, the ferrite phase shifters were developed, and the first phased-array antenna was designed, manufactured, and examined. Figure 1 shows[3] the mock-up of the

[1]This is now St.-Petersburg Electrotechnical University. The University was founded in 1886, as a Telegraph Engineer College. It was transformed, in 1898, into the Electrical Engineering Institute, with a five-years period of education, and in 1992, it was given the status of the Electrotechnical University. The St.-Petersburg Electrotechnical University now has about 7000 students, 1000 Lecturers and Professors, and numerous research groups, working in the fields of Radio Engineering, Electronics, Electrical Engineering, Computer Science, Solid State Physics, and Materials Science.

[2] The control of the radiation pattern of an immobile antenna was realized by American engineer H. T. Friis (1925), and Soviet scientists P. N. Ramlau (1932) and A. A. Pistolkors (1938).

[3]Provided courtesy of the Museum of History of St.-Petersburg Electrotechnical University.

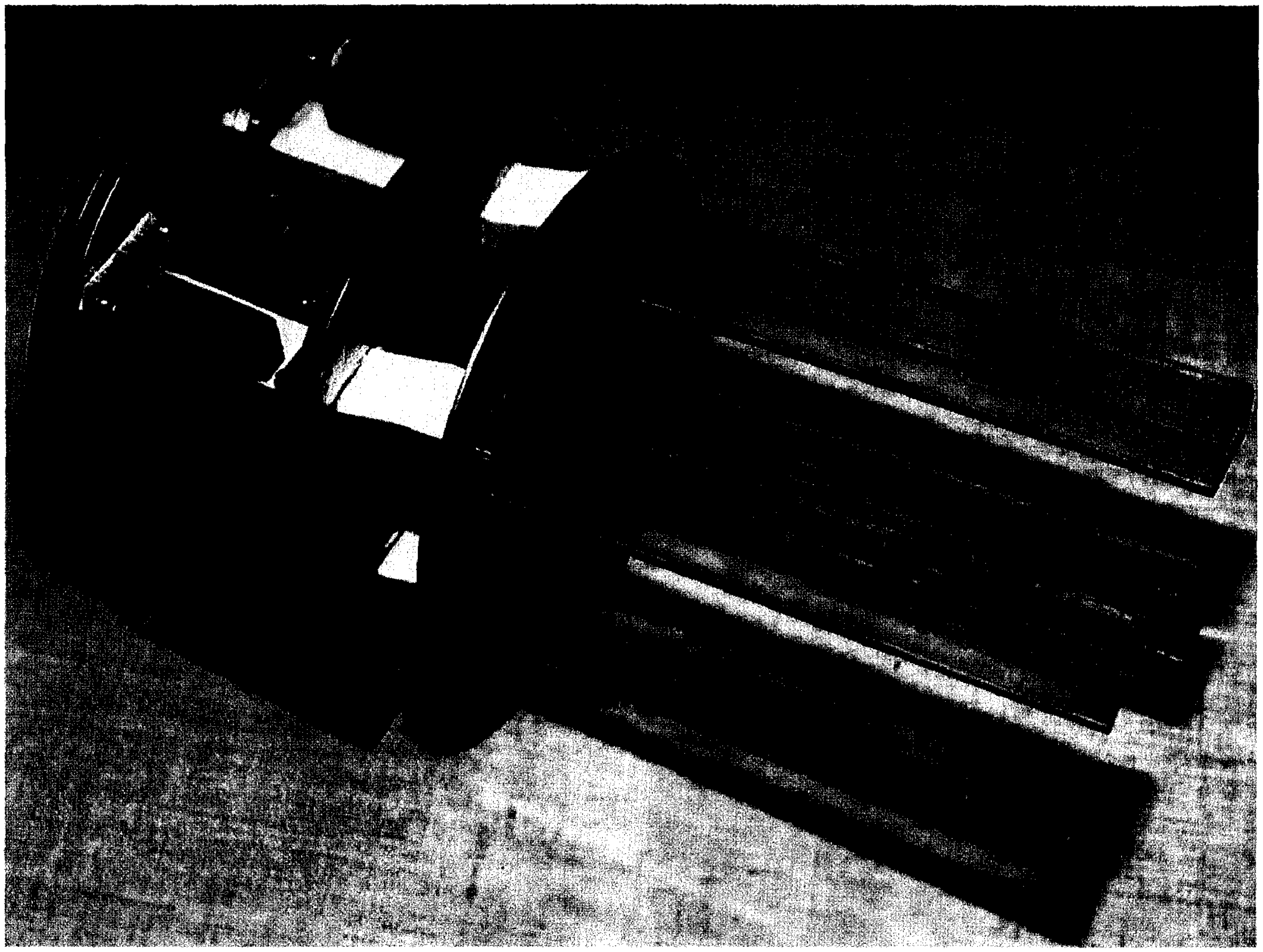

Figure 1. The first laboratory version (1955) of a phased-array antenna, providing a higher-speed conical rotation of the radiation pattern (courtesy of the Museum of the History of St. Petersburg Electrotechnical University.

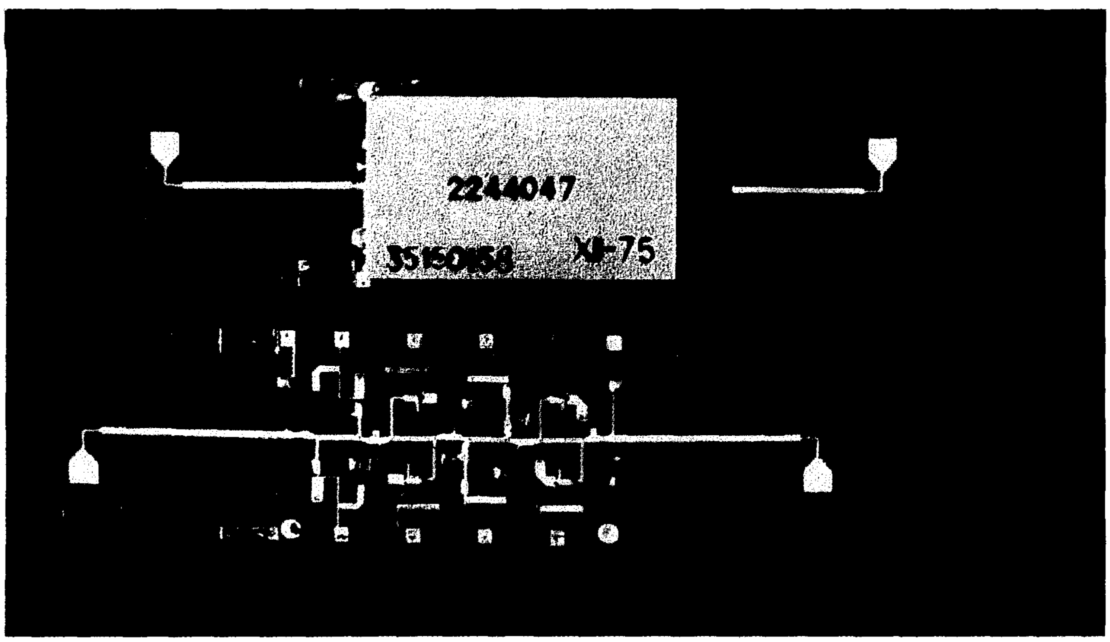

Figure 4. A hybrid microwave integrated circuit for a four-bit digital phase shifter, based on p-i-n diodes [13].

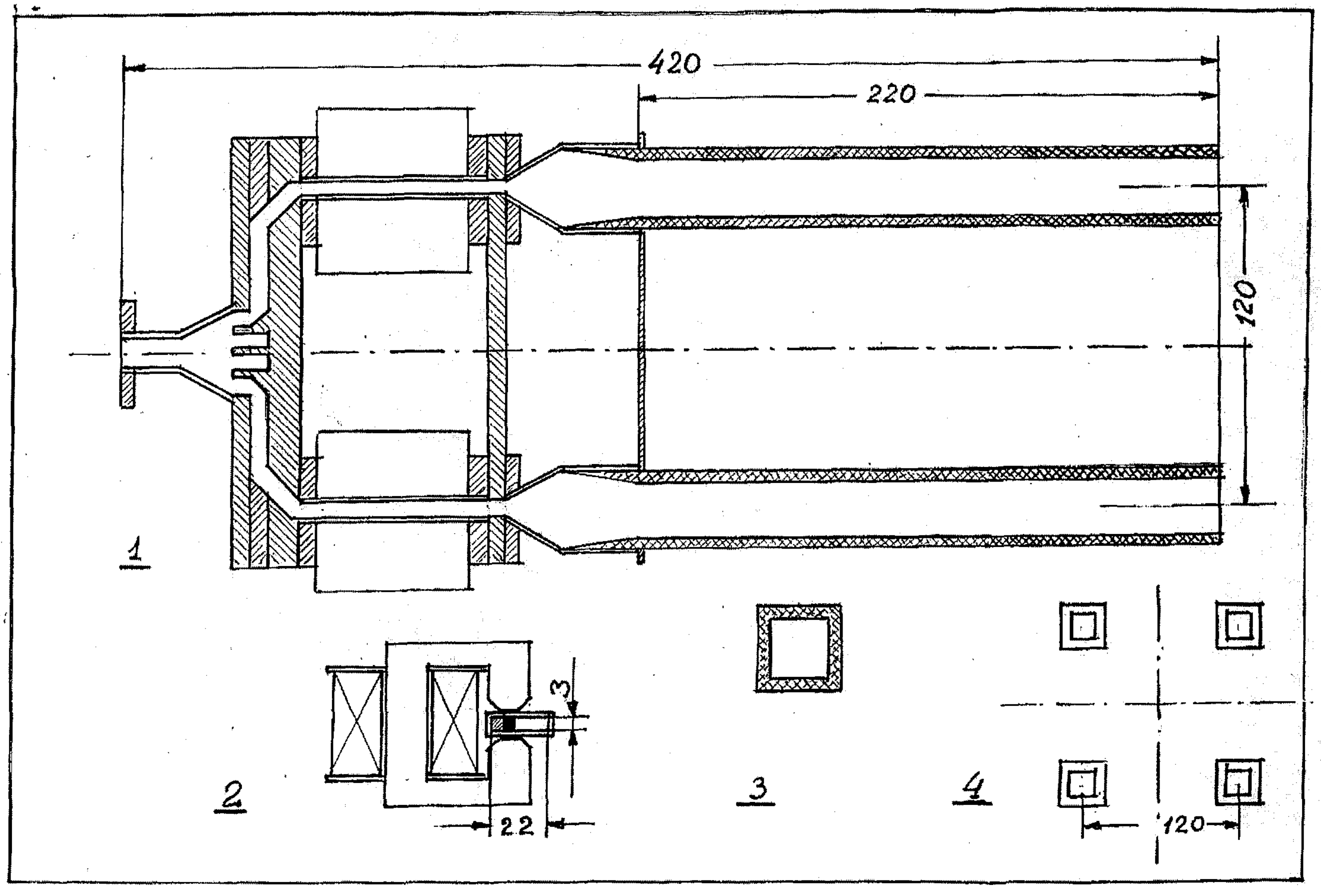

Figure 2a. A Schematic of the four-antenna phased array, shown in the photograph of Figure 1: (1) a schematic of the whole array; (2) the cross section of the ferrite phase shifter (the low-height waveguide, partially filled with dielectric and ferrite slabs); (3) the cross section of the dielectric radiator; (4) the configuration of the array.

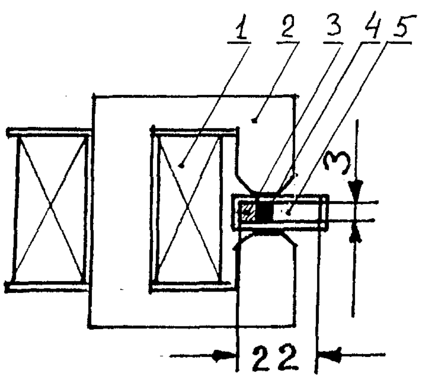

Figure 2b. The cross section of the ferrite phase shifter from Figure 2a. Item (1) is the coil (winding); (2) is the magnetic armature; (3) is the dielectric slab; (4) is the ferrite slab; and (5) is the rectangular waveguide.

phased-array antenna, which was presented to the Ministry Commission in June, 1955. One of the Commission members was Professor Lev D. Bakhrakh, who vigorously supported, at that time, research concerning electronically scanned antennas. During several successive decades, he played an essential role in developing different kinds of antenna systems in the Soviet Union. Professor Bakhrakh is the living witness to the success of Yurov's group in 1955. In literature, the phased-array antenna was referenced only in 1986 [2]. As far as we could investigate the literature[4], the first publication about microwave ferrite phase shifters appeared at the end of 1954 [3], and some versions of phased-array antennas were described in 1956-1957 [4].

Dr. Yuri Yurov (1914-1995) was elected Professor of the Department of Radio Engineering in 1953, and became the Head of the Department in 1955. His academic and research activities were directed toward the study and development of microwave engineering. The theoretical foundation of microwave engineering was electrodynamics. Prof. Yurov organized a seminar for undergraduate and postgraduate students on the problems of electrodynamics with an academic level much higher than the level of the common student curriculum of that time. The work of the seminar made it possible to select the most important problems, and to collect a group of the most active students. One of the problems was the phased-array antenna. The problem was included in a project supported by a Government Program. In 1960, Prof. Yu. Yurov pre-

[4]Unfortunately, we do not know what was included in the American report, "Ferrite at Microwaves," Proc. Fourth Symposium on Scanning Antennas, NRL, Rep. 400, pp. 123-131, April, 1952, which has not been found in available publications.

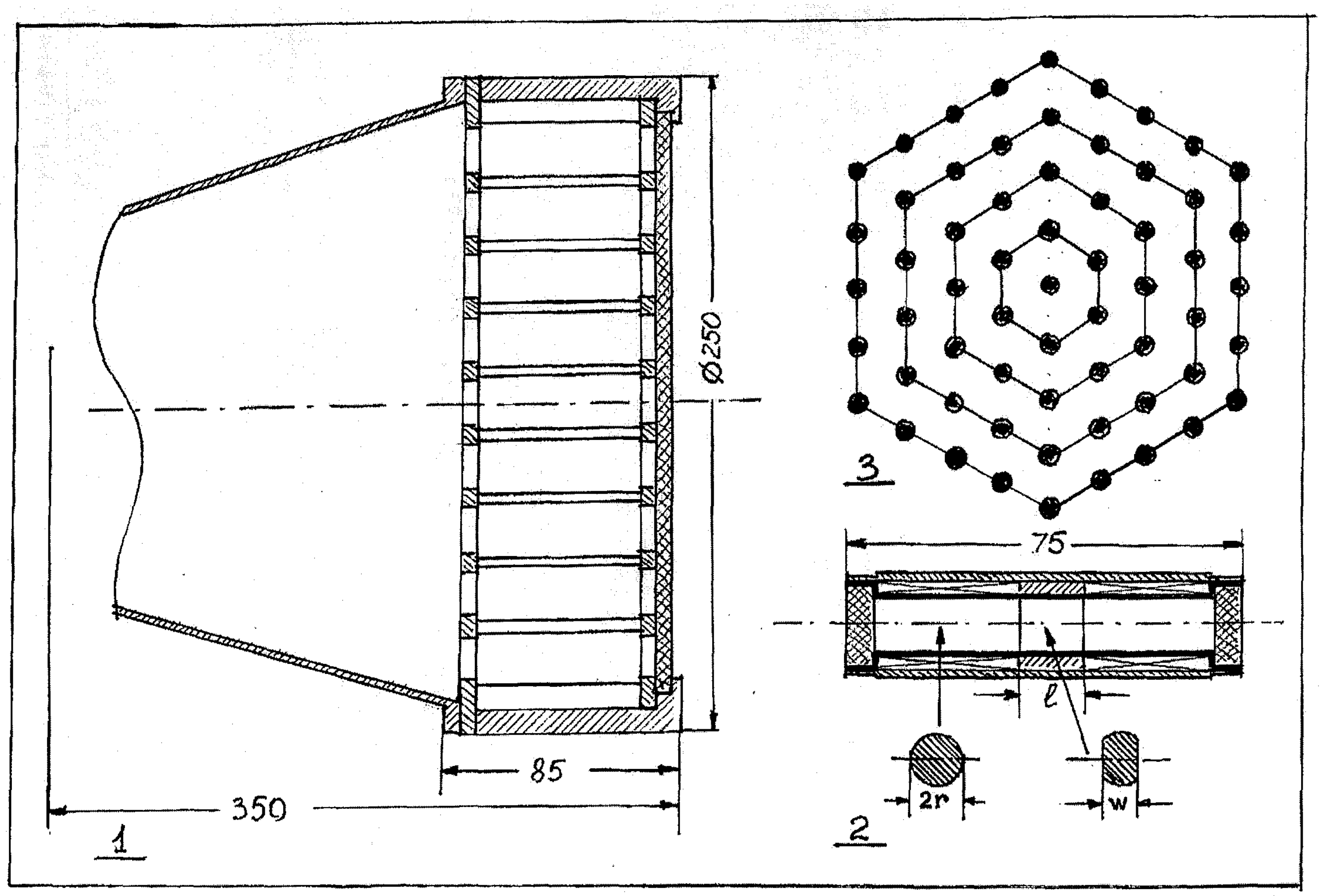

Figure 3a. A schematic of the 61-element phased-array antenna: (1) the cross section of the lens-type array, fed by a conical horn; (2) the cross section of the ferrite phase shifter; (3) the configuration of the array.

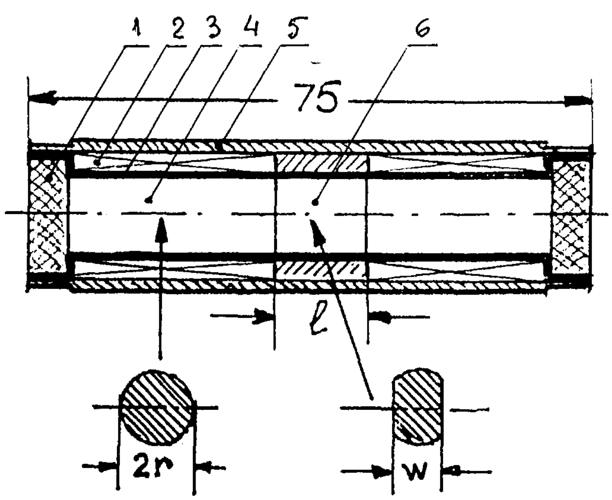

Figure 3b. The cross section of the ferrite phase shifter from Figure 3a. Item (1) is the cylindrical waveguide section, filled with dielectric ($\varepsilon = 7.5$); (2) is the coil (winding); (3) is the thin-wall brass tube; (4) is the ferrite filling the TE_{11} waveguide; (5) is the waveguide section filled with a dielectric slab of non-circular symmetry.

Table 1. The wave polarization and the phase differences for the phase shifter used with the phased-array antenna shown in Figure 3.

Wave Polarization		Phase Shift Along Section III	Wave Polarization		Total Phase Shift
Input of Section I	Output of Section I		Input of Section II	Output of Section II	
↑	→	0°	→	→	0°
↑	↑	90°	↑	→	90°
↑	←	0°	←	←	180°
↑	↑	90°	↑	←	270°

sented some results connected with microwave electrodynamics at the General Assembly of URSI in London. However, the main research achievements of Yurov's group were not available for open publication at that time.

Designing an electronically scanned antenna is comprised of two fundamental parts:

1. The selection of the number of radiators in the array and the determination of the array configuration; and

2. The design of the phase shifters, which control the phase distribution in the array.

Two students from the Electrodynamics Seminar were recruited for work with the phased-array antenna. They were Orest Vendik and Yuri Yegorov. In a few years, both of them published books describing the theory of the phased-array antenna [5], and the theory of partially filled waveguide structures, used as ferrite phase shifters [6].

2. Two Phased-Array Antennas Developed at the Electrical Engineering Institute

Figure 2 shows a schematic of the antenna presented in the photograph in Figure 1. The antenna was designed as a planar array of four dielectric radiators, fed through phase shifters included between the power splitter and the radiators. Figure 2b presents the cross section of the ferrite phase shifter. The size of the waveguide cross section was 3×22 mm^2. The configuration of the dielectric and ferrite insets provided a reciprocal phase shift in the range of 0 to 360°. The magnetic system was fulfilled using standard transformer-iron sheets. An electronic unit supplied the control current, in the frequency range of 1 to 10 kHz. The radiation pattern of the antenna was characterized by a beamwidth of 11-12°, with a sidelobe level below 15 dB. The cone of scanning was 10-12°. The insertion loss was not worse than 3 dB. The frequency range was 9-9.5 GHz. Such an antenna was intended for use in radar, for automatic tracking of targets.

Later, the group of Prof. Yurov developed a phased-array antenna with a much higher ratio of scanning angle and radiation-pattern beamwidth. In 1959, such an antenna was demonstrated. Figure 3 illustrates the schematic of that antenna. It was a conical horn, coupled to an artificial lens, formed as a system of ferrite phase shifters. The lens was comprised of 61 phase shifters, arranged in a hexagonal structure. The diameter of the lens' radiating aperture was 25 cm. The radiation pattern of the antenna was characterized by a beamwidth 7-8°, with a sidelobe level below 18 dB. The scanning of the antenna beam could be performed in two perpendicular planes, within the limits of 25°. The total insertion loss was not worse than 3 dB. The frequency range was 9-9.7 GHz. The most difficult problem in developing the lens of 61 phase-controllable radiators was designing the ferrite phase shifters. Attempts to replicate Regia-Spenser's phase shifter [4] were not successful. We were not able to obtain a repeatable and temperature-stable version of Regia-Spenser's phase shifter.

An original version of a quasi-reciprocal ferrite phase shifter, based on the Faraday effect, was suggested [7]. The phase shifter had a digital control, providing four states of phase shift: 0, 90, 180, and 270 degrees. Figure 3b illustrates the operating principle of the phase shifter, which was based on propagation of the H_{11} mode in a circular waveguide filled with ferrite. The phase shifter comprised three sections: two sections provided a rotation of the wave polarization through $\pm 90°$, and the third section was characterized by an effective length of $\pi/2$ and $3\pi/2$ for waves with orthogonal polarization. The wave polarization and the phase differences are shown in Table 1.

The phase shifter was enclosed in an iron screening cylinder. The magnetization of section I and section II was controlled by separate windings. It is worth noting that the electric length of the phase shifter differed by 180° for the waves propagating in different directions. That did not depend on the controllable phase shift, and did not influence the position of the antenna beam in the receiving or transmitting mode. The thin-wall brass tube was completely filled with ferrite. The diameter of the tube was 10 mm. At each end of the tube there was a $\lambda/4$ matching section, filled with a low-loss dielectric ($\varepsilon = 7.5$). The aperture of the sections played the role of radiators. The external surface of the lens was covered by a dielectric plate ($\varepsilon = 2.5$) with a thickness of 4 mm. The plate reduced the mutual coupling between the radiators. The frequency bandwidth of the phase shifter assembled with the radiators was about 20%, and the insertion loss was not worse than 1.5 dB. The response time of the phase shifter was about 3 ms, and was limited by the current induced in the brass wall of the waveguide.

3. Some Contributions to Phased-Array Antenna Theory

Concurrently with the design of the antenna, the members of Yurov's Group were doing theoretical work. Some theoretical results obtained in that period seem to be interesting. Two of these will be mentioned below.

3.1 Minimum Number of Emitters in a Phased-Array Antenna [8, 9]

If the beamwidth of the antenna is $\Delta\theta$ and the sector of beam scanning is θ_s, the minimum necessary number of emitters in a phased-array antenna is given by the formula

$$N = 1 + \frac{\theta_S}{\Delta\theta}. \tag{1}$$

This formula is analogous to the well-known sampling theorem, if θ_s is replaced by the duration of the signal, τ, and $\Delta\theta$ is replaced by $\Delta\tau$, the length of the shortest pulse that can pass through the circuit. A more-general formula for the necessary number of emitters in a phased-array antenna was derived by M. I. Kontorovich and V. Yu. Petrun'kin [10]:

$$N = \frac{\Delta\Omega_S}{4\pi} D, \tag{2}$$

where $\Delta\Omega_s$ is the solid angle of scanning, and D is the directive gain of the array.

3.2 Mutual Impedance of the Array Emitters [11]

The mutual impedance between two emitters entering the array is an important characteristic of the array itself. If the complex radiation patterns of two emitters are known, the mutual impedance between them can be found in the following way:

$$r_{i,j}(\omega) = \frac{15}{\pi\lambda^2} h_i h_j \int_{0,0}^{2\pi,\pi} \left[\Phi_i(\theta,\varphi)\Phi_j^*(\theta,\varphi) + \Phi_j(\theta,\varphi)\Phi_i^*(\theta,\varphi) \right] \sin\theta d\theta d\varphi, \quad (3)$$

where h_i is the effective length of the ith emitter, λ is the wavelength in free space, $\Phi_i(\theta,\varphi)$ is the complex radiation pattern of the emitter with the number i, and the argument of $\Phi_i(\theta,\varphi)$ is taken with respect to the common phase center of the array.

Evidently, $r_{i,j}$ is a function of frequency. Using the Kramers-Kronig relation, one can find the imaginary part of the mutual impedance:

$$x_{i,j}(\omega_0) = \frac{2\omega_0}{\pi} \int_0^\infty \frac{r_{i,j}(\omega)}{\omega^2 - \omega_0^2} d\omega - \frac{A}{\omega_0}, \quad (4)$$

where A is a constant responsible for quasistatic reactance of the emitter.

The simulation of the mutual impedance between emitters in an array made it possible to avoid blanks inside the scanning sector [5].

4. Conclusion

After forty years, it is interesting and instructive to set in order the pieces of memory about the heroic period (1955-1960) when the existence theorem of electronically scanned antennas was proven. The development of jet aircraft and the appearance of missiles turned phased-array antennas into a strategically important tool of electronic warfare. The ideas came out of university laboratories, and were transferred to industrial research centers. Much research was done in the Russian universities and research centers. A great organizing role was played by the world-wide-known expert in the field of antenna theory, Alexander A. Pistolkors [12], and many useful publications were made by M. B. Zakson and D. I. Voskresensky. The first phased-array antennas, based on ferrite phase shifters, were forced out by p-i-n diode phase shifters, which turned to be more compatible with microelectronic technology [13]. In order to show the development of microwave microelectronics during the period of 1960-1975, a photograph of a p-i-n diode phase shifter [13] is presented in Figure 4. The search for the original design is continuing. Ferroelectric phase shifters [14] can possibly be applied to some versions of the phased-array antenna. A combination of ferroelectrics and high-temperature superconductors [15] are promising for a cryoelectronic version of the phased-array antenna, which could be used in base stations of mobile-communication systems.

5. References

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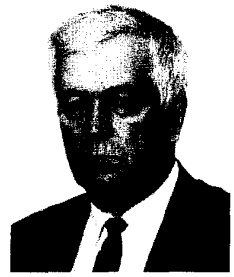
Introducing the Feature Article Authors

Orest G. Vendik was born in Leningrad in 1932. He received the Diploma of Radio Engineer (1954), Candidate of Science degree (1957), and Doctor of Science degree (1966), from the Electrical Engineering Institute (now the Electrotechnical University), St. Petersburg, Russia. He was involved in the projects associated with the phased-array antenna (1954-1964). He is the author of the book, *Antennas with Non-Mechanical Scanning* (in Russian; Moscow, Sovetskoye Radio, 1965). He was a researcher on leave at Surrey University, London, UK (1967-1968). He was the Head of the Department of Electron-Ion Technology (1969-1989) of the Electrotechnical University. Now he is a Professor and the Head of the Cryoelectronics Group of the Electrotechnical University. He works periodically as a Visiting Professor at Chalmers University of Technology, Gothenburg, Sweden. His research concentrates on applications of superconductors and ferroelectrics at microwave frequencies. Dr. Vendik is a recipient of the USSR State Prize for Science and Technology (1988). He was awarded the title of Honourable Man of Science of the Russian Federation (1999). He is a member of the St. Petersburg Association of Scientists (1989) and a member of the IEEE (1992).



Yuri V. Yegorov was born in Leningrad in 1930. He received the Diploma of Radio Engineer (1954), Candidate of Science degree (1964), and Doctor of Science Degree (1980) from the Electrical Engineering Institute (now the Electrotechnical University), St. Petersburg, Russia. He was involved in the projects associated with the phased-array antenna (1954-1964). He is the author of the book *Partially Filled Waveguides* (in Russian; Moscow, Sovetskoye Radio, 1967). He was the Head of the Department of Theoretical Foundations of Radio Engineering (1975-1997), and then a Professor of the Electrotechnical University. During this period, he concentrated on acousto-optical signal processing. Dr. Yegorov was awarded the title of Honourable Man of Science of the Russian Federation (1998). He was a member of the IEEE (1992-1999). Dr. Yegorov passed away suddenly in October, 1999.

Evolutionary Computation CD-ROM Tutorial

The IEEE Neural Networking Society and IEEE Educational Activities have released a CD-ROM tutorial entitled "Evolutionary Computation and Applications." The host of the tutorial is David B. Fogel, Editor-in-Chief of the *IEEE Transactions on Evolutionary Computation*. The tutorial serves as an introduction to evolutionary computation, supported by case studies from four expert practitioners and a roundtable discussion about practical implementation issues. The user is able to access sections by the following authors:

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- Dr. Mohamed El- Sharkawi, who presents evolutionary techniques for vulnerability assessment of power systems

- Dr. Piero Bonissone, who discusses hybrid soft computing systems using fuzzy logic and evolutionary algorithms

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