УДК 537.86:621.396.677.71

ELECTRICALLY SWITCHABLE, KA-BAND SLOTTED WAVEGUIDE ANTENNA ARRAY SYSTEM

S. S. Sekretarov, D. M. Vavriv, V. A. Volkov, M. P. Natarov*, V. V. Glamazdin*

Institute of Radio Astronomy of the National Academy of Science of Ukraine
4, Chervonopraporna St., Kharkov, 61002, Ukraine
E-mail: vavriv@radar.kharkov.com

** A. Usikov Institute of Radio Physics and Electronics of the National Academy of Science of Ukraine*
12, Ac. Proskura St., Kharkov, 61085, Ukraine
E-mail: natarov@ire.kharkov.ua

An original electrically switchable, K_a-band slotted waveguide antenna array system has been recently developed, produced, and tested. The system consists of four identical sections, which are connected to a radar transmitter/receiver by means of a high-power, multipole *p-i-n* switch. The introduced *p-i-n* switch enables for a fast electrical scanning of the antenna beam what essentially extends possible areas of the antenna system application. The antenna system is used in a helicopter collision avoidance, surveillance, and weather radar. This paper describes design features of the antenna system, its main characteristics, results of its testing, and the antenna integration in the radar. Figs. 9. Tabl. 1. Ref.: 4 titles.

Key words: slotted waveguide antenna, K_a-band antenna, *p-i-n* switch, collision avoidance radar.

In this paper, we describe an electrically switchable, K_a-band antenna array system, which has been designed for airborne radar applications. The system consists of four identical sections, which are slotted waveguide arrays. The sections are connected to a radar transmitter/receiver by means of a high-power, multipole *p-i-n* switch. The slotted waveguide arrays have been developed by using modern antenna simulation techniques and original approaches to the antenna design described in [1, 2]. The *p-i-n* switch used in the antenna system is the state-of-the-art device which is characterized by both a high commutated power – of about several kilowatts, and a rather low switching time – of about several microseconds.

The developed antenna system combines known advantages of slotted waveguide arrays, like high efficient, strength of the antenna construction, extended frequency operation range, high power operation capability, small dimensions and weight. The introduced *p-i-n* switch enables for a fast electrical scanning of the antenna beam what essentially extents possible areas of the antenna system application. So far, the antenna system has been successfully introduced in a helicopter collision avoidance, surveillance, and weather radar. The radar is intended for providing the flight safety of helicopters, including detection of wires of power lines and other obstacles, monitoring of meteorological conditions on the direction of flight, and providing a secure landing.

1. Design of the antenna section. Each individual section of the antenna system is produced as a slotted antenna array made of rectangular waveguides, as shown in Fig. 1. The section consists of a collection of nine identical linear radiating arrays. Longitudinal slots are arranged in the broad wall of the radiating waveguides. The radiating waveguides are fed via inclined coupling slots from a crossed feeding waveguide. In order to realize a wideband antenna operation, the arrays operate in a non-resonant (travelling-wave) radiating mode. The feeding waveguide is a resonant (standing-wave) device.

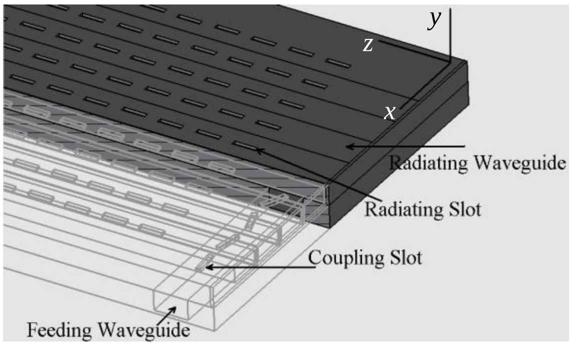


Fig. 1. Antenna construction

The *H*-plane radiation pattern is determined by that of the single radiating waveguide, whereas the *E*-plane pattern is defined by feeding of the radiating waveguides. According to the work [1], we synthesize the radiation pattern in both planes by using the following amplitude distribution:

$$U_n = \mu + \left(1 - \alpha\beta\left(\frac{n-N-1}{N}\right)^2\right) \times \\ \times \exp\left(-\beta\left(\frac{n-N-1}{N}\right)^2\right), \quad (1)$$

where U_n is the normalized amplitude at the *n*-th slot; $2N-1$ is the number of slots, $\mu = 0{,}8$, $\alpha = 2{,}3$, $\beta = 0{,}85$. This distribution enables for the realization of radiation patterns having both maximal gain and minimal sidelobe level.

As an initial approximation, we synthesize the radiating array by using the energy method [3]. The dependence of the slot radiation coefficient $\alpha(x_1)$ versus the slot offset from the waveguide centerline has been determined by using *FDTD*-simulations. So the slot offsets have been determined from the function $\alpha(x_1)$, which is shown in Fig. 2. It should be mentioned that the slot dimensions, used in our computations, were as follows: the length of 3.9 mm and the width of 0,8 mm. Such length is close to the slot resonant length at the frequency of 35.5 GHz.

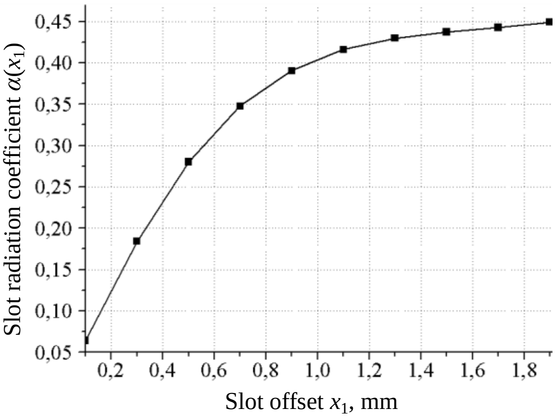


Fig. 2. Slot radiation coefficient versus the slot offset

The final values for the slot offsets have been obtained by using the *FDTD*-simulations. The performed synthesis has resulted in optimal slot offsets, which realize the needed amplitude distribution. The initial and optimal slot offsets are shown in Fig. 3. The difference between them shows the effect of mutual coupling of the radiating slots.

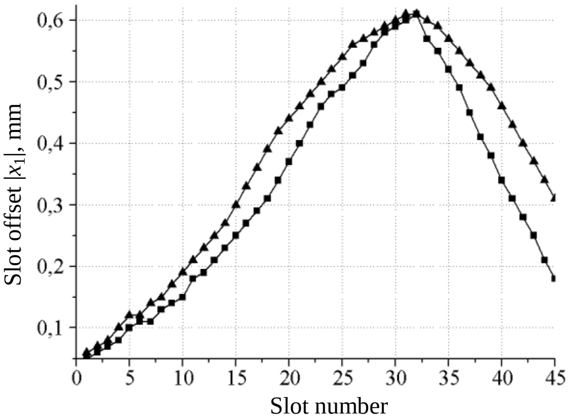


Fig. 3. First approximation for the slot offsets and that after the adjustment: ■ – energy method; ▲ – after adjustment

Neighboring slots are spaced at a distance of about $\lambda_g/2$, and so they have to be shifted at the opposite sides from the waveguide centerline to produce an additional phase shift of π for the required phase distribution.

The usage of the standard K_a-band waveguide in the antenna design is not acceptable because the *E*-plane slot spacing in this case is about the wavelength, and due to this, intensive grating lobes are excited. In order to overcome the problem, we have designed the plane array consisted of 9 linear slotted waveguides with the crossection of 5,5 mm over 2,5 mm and the wall thickness of 0,9 mm.

The energy distribution between the radiating waveguides is arranged by means of a crossed waveguide with inclined slots in the center of its broad wall. Such feeding is sufficiently compact, easy-to-design, and easy-to-make. The radiating waveguides are fed in-phase what is achieved by the half-of-wavelength slot spacing in the feeding waveguide along with the opposite in sign tilt of the neighboring slots. Such slot spacing is realized provided the feeding waveguide width is

$$a_f = \lambda_0/2\sqrt{1-\left(\lambda_0/\left(2\left(a_r+t\right)\right)\right)^2},$$

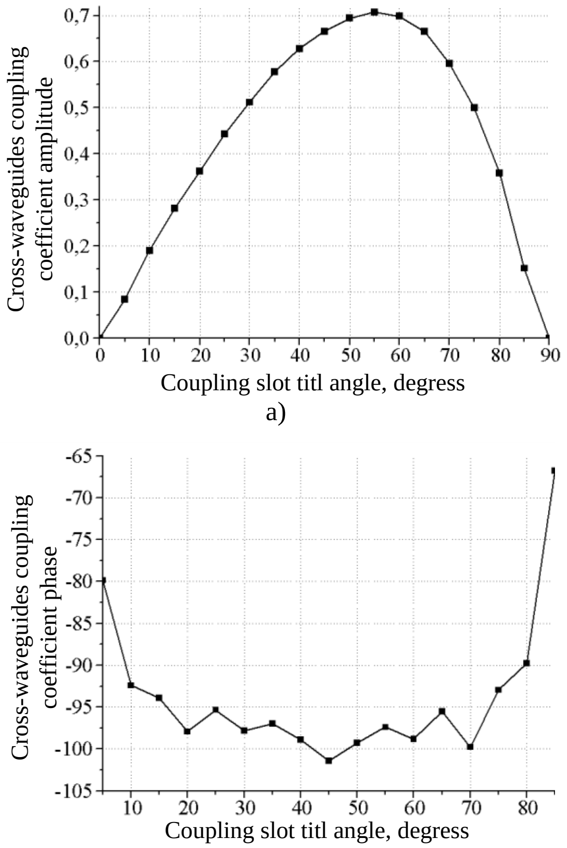
where t is the wall thickness between the radiating waveguides; a_f and a_r are the broad wall widths for the feeding and radiating waveguides, respectively. In accordance with this formula, the a_f-value is 5,77 mm.

The slot dimensions for the feeding waveguide have been selected as 4 mm over 0,8 mm. Again, *FDTD*-simulations have been used to calculate the coupling coefficient for the crossed waveguides. In Fig. 4, the coupling coefficient amplitude (a) and the phase (b) are shown as functions of the slot tilt angle measured with respect to the feeding waveguide axis.

The needed tilt angle for each of the coupling slots has been determined from Fig. 4 with the following adjustment by using of *FDTD*-simulations to realize the aperture distribution (1) in the *x*-direction.

As the final step of the antenna design, we have performed numerical simulations of the complete antenna structure, which include the plane array and the feeding system. These simulations have confirmed the correctness of the solution introduced.

The beam width realized by the antenna section is 10° in the *E*-plane and 2° in the *H*-plane. The section dimensions are 310×72×9 mm^3.



a)

b)

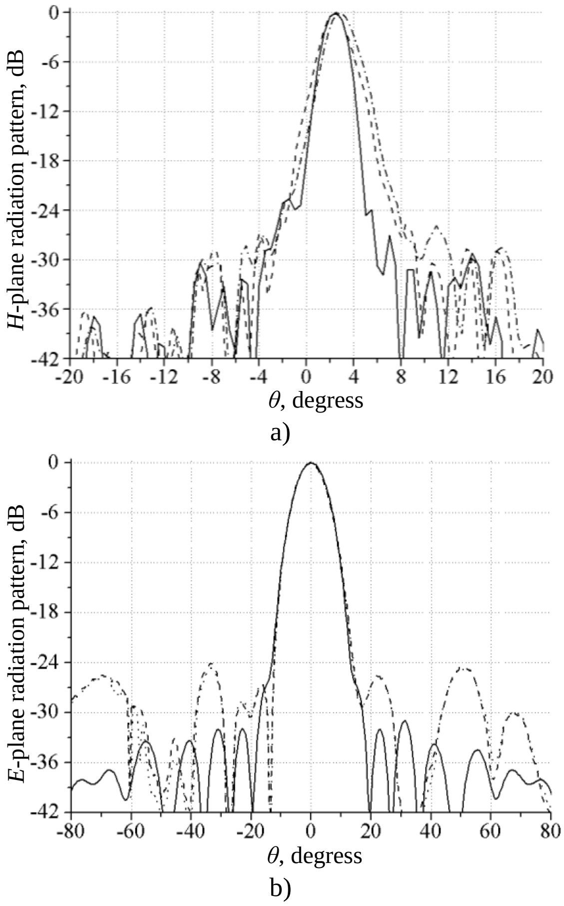
Fig. 4. Cross-waveguides coupling coefficient versus the slot tilt angle: a) amplitude; b) phase

2. Measurement results. The designed antenna sections have been fabricated by using metal coating, milling, electric-sparking, and laser welding technologies. These technologies allow for producing such antennas with rather high reproducibility of the antenna characteristics. We have also observed a rather high degree of compliance of the measured and simulated results. In Fig. 5, the corresponding comparison is shown for the radiation patterns in both planes.

Fig. 6 plots and compares the dependence of the *VSWR* on the operating frequency obtained from the theoretical and experimental results. The antenna demonstrates a rather low value of the *VSWR* in the prescribed frequency band what simplifies its matching with radar transmitter and receiver.

In order to protect the antenna from dust and moisture, a radome coating has been designed and introduced. The radome is made of a 4 mm foam sheet placed directly on the antenna radiating surface. The sheet is stabilized by means of 50 μm lavsan film. As it can be seen from Fig. 5, the radome exerts a rather small influence on the radiation pattern.

The main lobe of the pattern measured in the *H*-plane is a little wider (below the 3 dB level) than the calculated one. It is because of phase errors associated with the finite tolerance of the antenna fabrication. The level of sidelobes is as low as –23 dB what satisfy the design goal as well.



a)

b)

Fig. 5. Calculated and measured radiation pattern for designed plane slotted array: a) – *H*-plane; b) – *E*-plane.——— – calculated; - - - - – measured; —·—·· – measured with cover

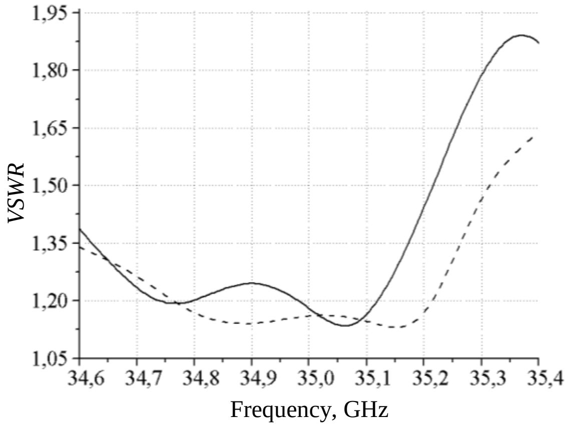


Fig. 6. ——— – calculated and —·—·— – measured *VSWR*

3. Antenna system. The complete antenna system consists of four independent slotted waveguide sections, which are shown in Fig. 7 integrated to a transmitter/receiver module of an airborne radar.

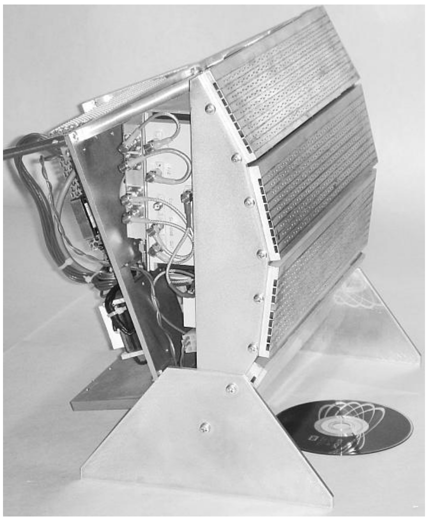


Fig. 7. A photo of the antenna system integrated to a transmitter/receiver module

Each antenna section forms the radiation pattern with the beamwidth of 10º in the elevation plane and 2º in the azimuth plane. The gain of each antenna section is over 30 dB. The antenna beams are displaced with the step of 16º in the elevation plane providing the total observation sector of about 60º as illustrated in Fig. 8.

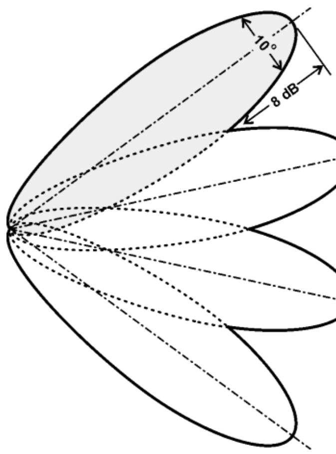


Fig. 8. Antenna pattern in the elevation plane

The sections are switched electrically by using an original high power reciprocal *SP*4*T* switch based on *p*-*i*-*n* diodes. The switch is based on three waveguide *Y*-junctions connected as a binary tree shown in Fig. 9.

The junctions of the second stage of the tree are ended by a reflective switches based on *p*-*i*-*n* diodes. Each switch utilizes two diodes included in resonant circuitry and operates in so-called inverse mode, when a high reflection occurs while the diode is biased in the reverse direction. The maximum peak power for such configuration is as high as 2,5 kW with the switching time as low as 1 μsec. It should be stressed that the proposed switch design minimizes the amplitude of the *RF* voltage across the diodes. The lengths of each branch of the *Y*-junctions are adjusted in order to optimize performance of the switch. The bandwidth of the switch is about ±3 %.

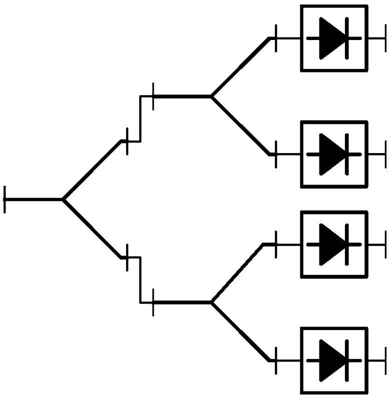


Fig. 9. A block-diagram of *SP*4*T* switch

Principal parameters of the antenna system are summarized in table below. The produced antenna along with other hardware and software solutions has enabled for achieving rather attractive characteristics of the complete radar system, which is the helicopter collision avoidance, surveillance, and weather radar [4].

Parameter	Value
Operation frequency range, GHz	35±0,2
Number of antenna sections	4
Antenna section switching	electrical
Antenna section switching time, μsec	2
Antenna switch decoupling, dB	> 25
Antenna switch insertion losses	<1,5 dB
Commutated pulsed power, kW	5 (max)
Commutated averaged power, W	5 (max)
Beam width of in *H*-plane, deg	2
Beam width of in *E*-plane, deg	10
Beam scanning range in *E*-plane, deg	60
Antenna gain, dB	>30
Sidelobe level, dB	<–20 dB
VSWR	<1,2
Dimension of the antenna section, mm^3	310×72×9
Weight of the antenna section, kg	0,3

Conclusions. An original electrically switchable, K_a-band antenna array system has been developed, produced, and tested. A high reproducibility of the antenna characteristics have been observed along with a high degree of their compliance with the simulation results. The antenna system has been designed for airborne application. It is used in a helicopter collision avoidance, surveillance, and weather radar.

The authors would like to thank A. Popov and L. Shevtsova for their valuable contributions to this work.

1. *Glamazdin V. V., Lukin K. A., Skresanov V. N.* Improvement of basic synthetic aperture pattern characteristic by comparison method // Radiophisics and Electronics. – 2005. – 10, No. 1. – P. 77-84.
2. *Sekretarov S. S., Vavriv D. M., Natarov M. P., Glamazdin V. V.* Development of a *Ka*-band slotted antenna array / Proc. of MSMW’07, Kharkov. – 2007. – 2. – P. 672-674.
3. Antennas and Microwave Devices (Design of the Phase Antenna Arrays) / Editor D. I. Voskresenskiy. – Moscow.: Radio and Sviaz. – 1981. – P. 432 (in Russian).
4. *Volkov V. A., Vavriv D. M., Kozhin R. V. et al.* A K_a-band, magnetron based scanning radar for airborne applications / Proc. of EUMW 2007, Munich – 2007. – P. 1465-1468.

ВОЛНОВОДНО-ЩЕЛЕВАЯ АНТЕННА, СИСТЕМА K_a-ДИАПАЗОНА С ЭЛЕКТРИЧЕСКИМ СКАНИРОВАНИЕМ ЛУЧА

С. С. Секретарев, Д. М. Ваврив, В. А. Волков,
М. П. Натаров, В. В. Гламаздин

В работе представлена оригинальная конструкция волноводно-щелевой антенной системы K_a-диапазона с электрическим сканированием луча. Система состоит из четырех одинаковых секций, которые подключены к приемо-передатчику через мультипольный *p-i-n* переключатель большой мощности. Предложенный *p-i-n* переключатель позволяет осуществлять быстрое электрическое сканирование луча антенны, что существенно расширяет область применения антенной системы. Разработанная антенная система была применена в радаре, предназначенном для обеспечения безопасности полета вертолетов, а также контроля метеоусловий. В статье описаны свойства антенной системы, приведены ее основные характеристики, результаты тестирования и интеграции антенны в радар.

Ключевые слова: волноводно-щелевая антенна, антенна K_a-диапазона, *p-i-n* переключатель, радар обеспечения безопасности полетов.

ХВИЛЕВІДНО-ЩІЛИННА АНТЕНА, СИСТЕМА K_a- ДІАПАЗОНУ З ЕЛЕКТРИЧНИМ СКАНУВАННЯМ ПРОМЕНЯ

С. С. Секретарьов, Д. М. Ваврів, В. А. Волков,
М. П. Натаров, В. В. Гламаздін

У роботі представлено оригінальну конструкцію хвилевідно-щілинної антенної системи K_a-діапазону з електричним скануванням променя. Система складається з чотирьох однакових секцій, які підключені до приймача-передавача через мультипольний *p-i-n* перемикач великої потужності. Запропонований *p-i-n* перемикач дозволяє здійснювати швидке електричне сканування променя антени, що істотно збільшує сферу застосування антенної системи. Розроблену антенну систему було застосовано в радарі, призначеному для забезпечення безпеки польоту гелікоптерів, а також контролю метеоумов. У статті описано властивості антенної системи, наведено її основні характеристики, результати тестувань та інтеграції антени в радар.

Ключові слова: хвилевідно-щілинна антена, антена K_a-діапазону, *p-i-n* перемикач, радар забезпечення безпеки польотів.

Рукопись поступила 3 июня 2008 г.