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Article

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DEVELOPMENT OF A MICROWAVE RESONANT WAVEGUIDE SLOT ANTENNA WITH IN-PHASE SLOT EXCITATION

The object of research in the work is the process of radiation of electromagnetic waves of a resonant waveguide-slot antenna with in-phase excitation of slots. The subject of research is the wave parameters and directional properties of a resonant slotted waveguide antenna with in-phase slot excitation. The existing problem is that it is necessary to ensure highly directional properties of the antenna with electrical control of its wave parameters at high transmitter power. This problem is due to the fact that to solve the problem of developing equipment for radio control, and radar of aircraft, highly directional antennas of small sizes are required. To solve this problem, the paper proposes the design of a simple and cheap version of a microwave resonant waveguide-slot antenna with in-phase slot excitation.

As a basis for developing a resonant slotted waveguide antenna, the authors chose a standard R48 rectangular waveguide, which is a classic in the theory of directional systems in the microwave range. This is due to the fact that in order to calculate and study a microwave resonant waveguide-slot antenna with in-phase excitation of slots, the authors used well-known elements of the theory of aperture antennas. The design of a resonant slotted waveguide antenna consists of a rectangular waveguide, an exciter, and a feeder. The radiation surface of the antenna is a wide wall of a standard R48 rectangular waveguide along the central axis, of which slots are symmetrically cut in a checkerboard pattern. The exciter is made in the form of a metal pin inside a rectangular waveguide near the short-circuited wall. This pin acts as an asymmetric vertical vibrator that excites electromagnetic waves in a rectangular waveguide. The antenna is tuned to the maximum radiation power mechanically by moving the short-circuited wall of the rectangular waveguide. The pin feeds a feeder based on a coaxial cable with a characteristic impedance of 75 Ohm.

The developed resonant waveguide-slot antenna with in-phase excitation of slots operates in the frequency range of 4.0–6.0 GHz. In the frequency range of 4.0–5.45 GHz, the value of Voltage Standing Wave Ratio (VSWR) varies from 1.08 to 2.1. In the frequency range of 5.45–6.0 GHz, the Voltage Standing Wave Ratio (VSWR) value varies from 2.1 to 6.55. The directivity of the antenna in the operating frequency range is not less than 90. The width of the main lobe of the antenna pattern in the horizontal plane is not more than 3.1°. The antenna gain in the operating frequency band is at least 100. The efficiency is at least 90 % with a maximum generator signal power of 10 kW.

Keywords: *resonant antenna, waveguide-slot antenna, frequency range, voltage standing wave ratio, radiation pattern.*

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1. Introduction

The functioning of radioelectronic and radiotechnical systems is related to the long-distance transmission of information carried by electromagnetic waves. Therefore, radio equipment must have one or more antennas [1].

Antennas are electromagnetic energy converters [1]. The transmission antenna is designed to convert the energy of electromagnetic waves coming from the feeder into the energy of electromagnetic waves in space and their radiation in given directions [1]. The receiving antenna performs reverse functions [2]. It isolates electromagnetic waves coming from certain directions in space and transforms their energy into the energy of electromagnetic waves that propagate through the feeder to the receiver [2].

Modern antennas not only emit or receive electromagnetic waves. Modern transmission antennas ensure the necessary distribution of the electromagnetic field in space during radiation [3]. Modern receiving antennas carry out primary processing of received electromagnetic waves [3]. The development of transmitting and receiving antennas is not limited to solving the problems of ensuring their required wave properties in a given frequency range [3]. The main requirement for modern transmitting and receiving antennas is the ability to electrically control their parameters and characteristics [3].

Antennas are reverse devices [1–3]. They must work in both transmitting and receiving modes. At the same time, the antenna wave parameters and characteristics of the antennas must be constant both in the transmitting and receiving modes. At the current stage of the development of radio frequency technology, the task of developing powerful antennas in the centimeter frequency range for aviation flight support equipment is urgent [3]. Such antennas should have good directional properties, the ability of electrical control, ease of manufacture, and be highly reliable in operation [3].

Waveguide-slot antennas, which are mainly used in centimeter ranges, have become widespread [4]. They are used in the radio equipment of aircraft due to their compactness, small weight and dimensions, as well as low aerodynamic resistance. Slots can be cut in the skin of the aircraft without deteriorating its aerodynamic performance.

One slot or a system of two or three slots provides weakly directed radiation [5]. Longitudinal slot antennas on a round cylinder are used in the meter wave range for radio broadcasting stations with frequency modulation [6].

The system, consisting of a large number of slots in the walls of the waveguide, is able to form a narrow directional pattern and ensure rapid oscillation of the radio beam. Such antennas are used in radar.

Most often, resonant slots are used, which are located differently on the wide or narrow walls of a rectangular waveguide with the H_{10} wave type [6].

Any radiating gap loads the rectangular waveguide and affects its mode of operation. Part of the power propagating along the waveguide is radiated by the slot, part of the power is reflected back to the generator, and part of the power passes further [7].

Unidirectional, weakly directional and multidirectional slot antennas are used [8]. In aviation technology, in addition to waveguide-slot antennas with a spatially fixed directional pattern, antennas with mechanical, electromechanical and electrical scanning are used.

An important advantage of waveguide-slot antennas is the ability to oscillate (scan) the beam by changing the phase velocity in the waveguide [8].

Known methods of electrical (frequency) scanning for waveguide-slot phased antenna arrays. These methods are used for the classical design of antennas based on volumetric rectangular waveguides [6]. Another promising direction in the development of slot antenna technology is the development of designs based on printed circuits and strip lines [9, 10].

One of the promising areas of modern antenna technology is the improvement of antenna array scanning methods, in particular those that provide the possibility of wide-angle scanning [10]. Scanning is carried out using either discrete or analog phase shifters (phase scanning) and by changing the frequency (frequency scanning).

The implementation of phase scanning in many multi-element arrays requires a large number of relatively expensive phase shifters, which leads to a significant increase in the mass and cost of the design, and also complicates control. In addition, effective phase shifters have not been developed and mastered by industry for all frequency ranges, due to which the search for alternative scanning methods continues to attract the attention of antenna array developers [6].

The method of frequency scanning does not have such disadvantages, however, in its traditional implementation; the frequency is used as a control parameter, which is a limiting factor from the point of view of optimal reception and immunity. That is why the development of scanning methods, which are characterized by the advantages of the frequency method and are free from its characteristic limitations, is a practically important task [6].

Waveguide-slot antennas find practical application mainly in the ultra-high frequency range, although in principle they can be used at lower frequencies as well. The main field of application of waveguide-slot antennas is radar and radio navigation [11].

Among the advantages of waveguide-slot gratings, the following can be distinguished:

– since there are no protruding parts, the radiating surface of the waveguide-slot antenna can be combined with the external contours of the aircraft body, without introducing additional aerodynamic resistance (onboard antenna);

– optimal directional diagrams can be implemented in such antennas, since the distribution of the field in the opening can be chosen within wide limits due to changing the connection of the emitters with the waveguide;

– the slot antenna has a relatively simple exciting device, and in addition, it is easy to operate [11].

The disadvantage of waveguide-slot antennas is the limitation of range properties. When the frequency changes in the non-scanning waveguide-slot antenna, the beam deviates in space from the given position, which is accompanied by a change in the width of the directional pattern and its alignment with the feeding feeder [11].

Thus, today the development of waveguide-slot antennas is an urgent task, which is connected with the rapid development of radar, radio navigation and radio communication, where these antennas are widely used.

The purpose of the work is the development and research of a resonant waveguide-slot antenna with in-phase excitation of the slots for a wide range of frequencies from 4.0 GHz to 6.0 GHz. To achieve the set goal, the following tasks must be solved:

– to carry out a numerical calculation of the parameters of the resonant waveguide-slot antenna;

– to develop a design of a resonant waveguide-slot antenna;

– to obtain the results of studies of the directional pattern and wave parameters of the resonant waveguide-slot antenna in the working frequency range.

2. Materials and Methods

The slot cut in the wall of the waveguide (Fig. 1) simultaneously works in the mode of reception and radiation, since in relation to one space (for example, to the internal space of the waveguide for a transmitting slot antenna), the slot is a receiving antenna, and in relation to another space (external) slot is a transmitting antenna. In this regard, the calculation of the input conductivity of the gap is difficult.

The radiation conductivity of the gap is calculated according to the formula [6]:

$$G = \frac{Z_A}{2(60\pi)^2}, \quad (1)$$

where Z_A – the wave resistance of the antenna.

The input conductivity (input resistance) of the slot determines the mode of operation of the waveguide. For resonant slots (Fig. 2), with a length close to half the wavelength and longitudinally cut, the normalized input conductance is determined as [11]:

$$g_{in} = 2.09 \cdot \frac{a}{b} \frac{\Lambda}{\lambda} \cos^2\left(\frac{\pi}{2} \frac{\Lambda}{\lambda}\right) \sin^2\left(\frac{\pi x}{a}\right), \quad (2)$$

where a and b are the width of the waveguide walls; Λ – the wavelength in the waveguide; x – the displacement of the slot relative to the middle line on the wide wall of the waveguide.

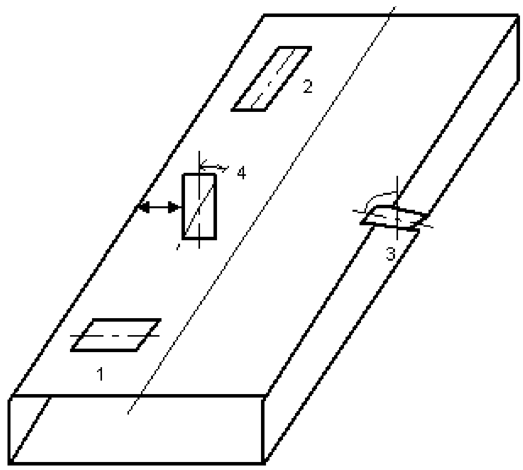


Fig. 1. Variants of radiated slots on the surface of a rectangular waveguide: 1 – transverse slot, which is excited by longitudinal currents on the wide wall of a rectangular waveguide; 2 – longitudinal slot, which is excited by transverse currents on the wide wall of the rectangular waveguide; 3 – a slot cut at an angle on the narrow wall of a rectangular waveguide, excited by a transverse current of constant amplitude; 4 – an inclined combined slot cut at an angle of inclination on the wide wall of a rectangular waveguide is excited by both transverse and longitudinal currents

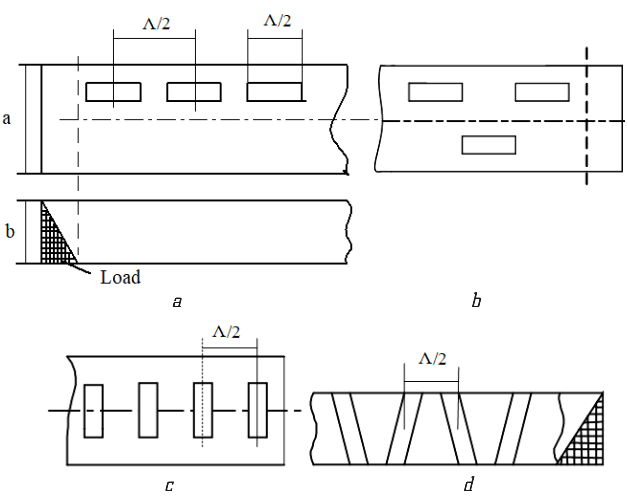


Fig. 2. Variants of resonant waveguide-slot antennas with in-phase excitation of neighboring slots: *a*, *b* – with longitudinal slots in the wide wall of the waveguide; *c* – with transverse slots in the wide wall of the waveguide; *d* – with inclined slots in the narrow wall of the waveguide

The normalized resistance value of the transverse gap is equal to [11]:

$$r_{in} = 0.523 \cdot \left(\frac{\Lambda}{\lambda}\right)^2 \frac{\lambda^2}{ab} \cos^2\left(\frac{\pi}{4} \frac{\lambda}{a}\right) \cos^2\left(\frac{\pi x}{a}\right). \quad (3)$$

The equation of the directional pattern of the waveguide-slot antenna consists of two coponents [11]:

$$f(\theta,\varphi) = F_1(\theta,\varphi) \cdot f_s(\theta), \quad (4)$$

where $F_1(\theta,\varphi)$ is the single-slot pattern; $f_s(\theta)$ is the system multiplier.

The normalized directional pattern of the waveguide-slot antenna is determined by formula (4).

The term $F_1(\theta)$ does not change much when the angle θ changes. Therefore, the spatial characteristic of the system is mainly determined by the system multiplier $f_s(\theta)$:

– for plane E [11]:

$$F_1(\theta) = 1, \quad (5)$$

– for plane H [11]:

$$f_s(\theta) = \frac{\cos(kl \cdot \sin\theta) - \cos kl}{\cos\theta}, \quad (6)$$

where the angle θ is counted from the perpendicular to the slot plane. Assuming that all antenna slots are excited with the same intensity, for an equidistant system [11]:

$$f_s(\theta) = \frac{\sin\left[\frac{n}{2}(kd \cdot \sin\theta - \psi)\right]}{\sin\left[\frac{1}{2}(kd \cdot \sin\theta - \psi)\right]}, \quad (7)$$

where n – the number of slots; d – the distance between the slots; ψ – the phase shift of the oscillations that excite adjacent slots.

For a resonant gap of length $\Lambda/2$ [11]:

$$F_1(\theta) = \frac{\cos\left(\frac{\pi}{2}\sin\theta\right)}{\cos\theta}. \quad (8)$$

The system multiplier for a resonant waveguide-slot antenna is also simplified [11]:

$$F_s(\theta) = \frac{\sin\left(\frac{nkd}{2}\sin\theta\right)}{n\sin\left(\frac{kd}{2}\sin\theta\right)}. \quad (9)$$

The deviation of the direction of maximum radiation from the normal to the opening of a non-resonant waveguide-slot antenna is determined from the condition [11]:

$$kd\sin\theta_m - \psi = 0, \quad (10)$$

where

$$\theta_m = \arcsin\frac{\psi}{kd}. \quad (11)$$

The phase shift ψ is calculated from the wavelength in the waveguide Λ and the distance between the slots. For a system with identical placement of slots (directphase excitation), which does not lead to the appearance of additional phase shifts [11]:

$$\psi = \frac{2\pi}{\Lambda} d - 2\pi, \quad (12)$$

and the angle θ_m:

$$\theta_m = \arcsin\left(\frac{\lambda}{\Lambda} - \frac{\lambda}{d}\right). \quad (13)$$

If the slots are placed alternately on both sides of the middle line, then the oscillations that excite the slots acquire an additional phase shift (phase-shift excitation). Therefore [11]:

$$\psi = \frac{2\pi}{\Lambda} d - \pi. \quad (14)$$

The deviation of the maximum radiation from the normal is the angle:

$$\theta_m = \arcsin\left(\frac{\lambda}{\Lambda} - \frac{\lambda}{2d}\right). \quad (15)$$

As follows from formulas (13) and (15), the direction of maximum radiation also depends on the frequency of oscillations and on the wavelength in the waveguide.

The coefficient of directional action of the waveguide-slot antenna can be approximately estimated by the formula:

$$D \approx 3.2 \cdot n,$$

where n – the number of slots.

The efficiency of waveguide-slot in-phase antennas is very high and is in the range of 80–95 %. With a large number of slots, the efficiency of waveguide-slot in-phase antennas has a value of 0.90–0.95.

3. Results and Discussion

The main element of the waveguide-slot antenna is a rectangular waveguide. The geometric dimensions of its cross-section determine the frequency range and mode of excitation of electromagnetic waves. A rectangular waveguide must work in the standing wave mode. For this, it is closed with a special piston. The slots are cut at such distances to ensure that their excitation is in-phase. The R48 rectangular waveguide was chosen for the frequency range and power. The technical parameters of the R48 rectangular waveguide are given in the Table 1.

The design of the waveguide-slot antenna is shown in Fig. 3. Electrical calculations were carried out, according to which the following basic parameters of the waveguide-slot antenna were determined. Number of radiating slots $n=23$. The resonant length of the slots is 35 mm. Longitudinal arrangement of slots in the wide wall of the waveguide in a staggered order at a distance of $\Lambda/2=50$ mm, and at a distance of $x=15$ mm from the edge of the wide wall of the rectangular waveguide. The width of the slots is 1 mm chosen to ensure the stability of the antenna against the breakdown of the air dielectric at the critical value of the electric field strength of 30 kV/cm.

The longitudinal slots are placed symmetrically relative to the longitudinal axis of the wide wall of the rectangular waveguide. Excitation of the slots is achieved with the help of a pin. The pin is an asymmetric vibrator oriented parallel to the vector E.

Table 1

Technical parameters of R48 rectangular waveguide

Type of waveguide	Nominal sizes		Critical frequency of the H_{10} wave, GHz	The operating frequency range is 1.25–1.9f_{cr}, for the H_{10} wave, GHz		Nominal frequency 1.5f_{cr}, GHz	Theoretical attenuation for copper at 1.5f_{cr}, dB/m	Breakthrough power, MW	Nominal wall thickness S, mm
	a	b							
R48	47.55	22.15	3.152	3.94	5.99	4.73	0.0355	1.17	1.63

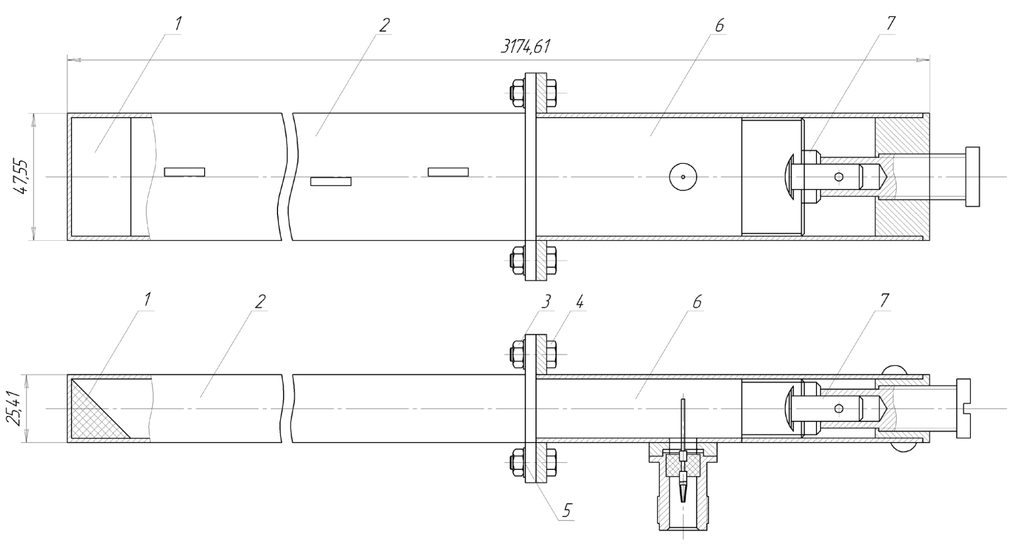


Fig. 3. Design of the waveguide-slot antenna: 1 – load; 2 – rectangular waveguide; 3 – bolt; 4 – nut; 5 – puck; 6 – excitation device; 7 – movable piston with a short-circuited wall

By specially selecting the length of the pin and the distance from the pin to the shorting wall, let's ensure the necessary alignment of the antenna with the coaxial waveguide. That is, let's obtain a traveling wave in a coaxial line with a H_{10} type traveling wave in a rectangular waveguide. The dielectric washer that fixes the position of the pin in the waveguide is a part of the coaxial connection. The diameter of the washer is taken equal to $\Lambda/4$. The active part of the pin resistance in the waveguide is equal to the radiation resistance. It is also equal to the impedance of the coaxial feeder feeding the pin, which is 75 Ohm.

Parameters of the excitation device for the waveguide-slot antenna in Fig. 3 such:

– The position of the pin in the waveguide relative to the wide wall of the rectangular waveguide is 23.77 mm.
– The length of the waveguide segment from the pin to the shortened wall (shortening piston) is 25 mm.
– The height of the pin is 11.2 mm.
– The effective height of the pin is 8.7 mm.
– The distance from the pin to the first slot to ensure the propagation of lower types of waves is 45 mm.
– The input impedance of the exciter at 4.0 GHz is 69.6 Ohm and at 6.0 GHz it is 53.5 Ohm.

Fig. 4 shows the graph of the dependence of the voltage standing wave ratio (VSWR – Voltage Standing Wave Ratio) on the wavelength in the operating frequency range. As can be seen from the graph in Fig. 4, acceptable values of the coefficient at the level of VSWR≤2.1 are provided for the wavelength range of 55–75 mm.

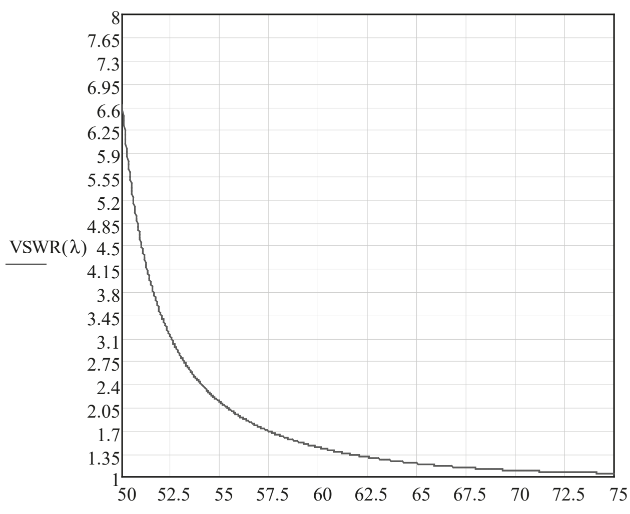


Fig. 4. Graph of the dependence of the standing wave coefficient on the wavelength in the working frequency range

An important wave parameter of the antenna is its input impedance. The input impedance is the load for the feeder that powers this antenna. The input resistance of the antenna is of great importance when setting the mode of operation of the feeder and generator. The power supplied to feed the antenna is determined by the input impedance and current modulus at the antenna input. The input resistance of the investigated waveguide-slot antenna is determined by the formula [11]:

$$R(f)=\frac{2\rho h^2}{a\cdot b}\cdot\sin^2\left(\frac{\pi}{a}\cdot x_1\right)\cdot\sin^2\left(\frac{2\pi f}{c}\cdot l_1\right), \quad (16)$$

where $\rho_w=538$ Ohm – the characteristic resistance of the R48 rectangular waveguide; $h=8.7$ mm – the effective height of the pin; $a=47.55$ mm and $b=22.149$ mm – dimensions of the cross-section of the R48 waveguide; $x_1=23.77$ mm – the position of the pin in the waveguide relative to the wide wall; $l_1=25$ mm – the length of the waveguide segment from the pin to the frozen wall.

The graph of the dependence of the input resistance of the proposed waveguide-slot antenna on the frequency is shown in Fig. 5.

The authors carried out a study of the directional diagram of the waveguide-slot antenna. In Fig. 6 shows the position of the angles θ and φ in space when the Cartesian coordinate system is entered relative to the emitted slot.

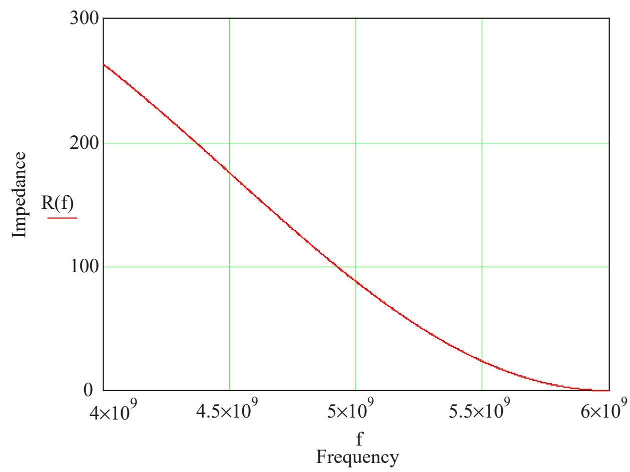


Fig. 5. Graph of the dependence of the input resistance of the waveguide-slot antenna on the frequency of the operating range

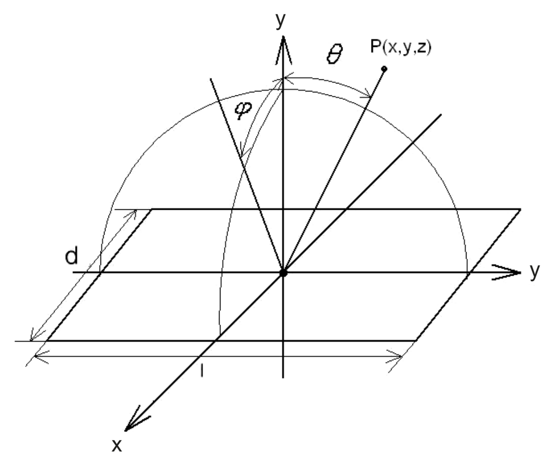


Fig. 6. Calculation of the angles θ and φ in space when calculating the directional diagram of the waveguide-slot antenna

The shape of the directional pattern of the waveguide-slot antenna is determined by the amplitude-phase distribution. In our case, the amplitude distribution is uniform, and the phase distribution is linear. The equation of the normalized directivity diagram of a linear array of identical emitters [11]:

$$F(\theta,\varphi)=F_1(\theta,\varphi)F_n(\theta,\varphi), \quad (17)$$

where $F_1(\theta,\varphi)$ is the directional pattern of one emitter; $F_n(\theta,\varphi)$ is the system multiplier. For the case of uniform amplitude and linear phase distribution, the system multiplier equation has the form [11]:

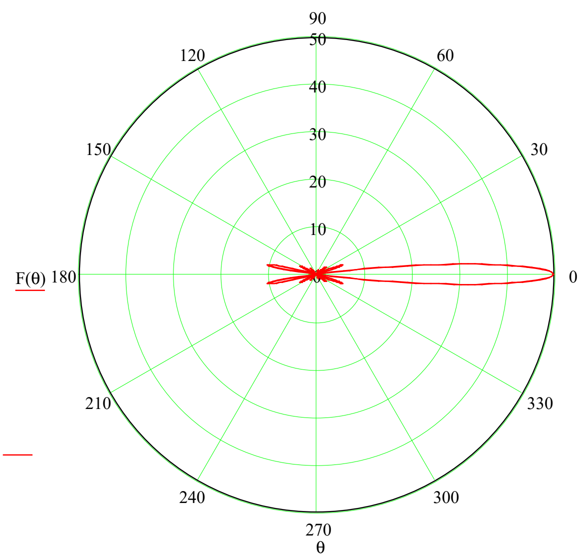
$$F_n(\theta)=\frac{\sin\frac{N}{2}\psi}{N\sin\frac{\psi}{2}}, \tag{18}$$

where $\psi = kd\sin\theta - \psi_1$ is the phase shift between the fields created at the observation point between adjacent emitters; $k=2\pi/\lambda$ is the phase constant of wave propagation; θ is the angle between the normal and the line of slots; ψ_1 is the phase difference of adjacent slots along the power supply system; N is the number of slots.

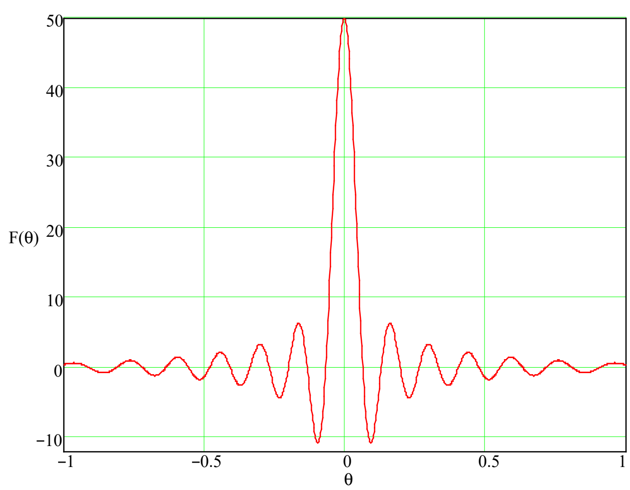
For a common-phase antenna $\psi_1=0$ [11]:

$$F_1(\theta)=\frac{\cos\left(\left(\frac{\pi}{2}\right)\cdot\sin\theta\right)}{\cos\theta}. \tag{19}$$

In the work, the authors investigated the directional diagrams of the waveguide-slot antenna in the frequency range of 4–6 GHz (Fig. 7–9). Fig. 6 and Fig. 9 show the directional diagrams of the waveguide-slot antenna in the polar and Cartesian coordinate systems at frequencies of 4.0 GHz and 6.0 GHz, respectively.



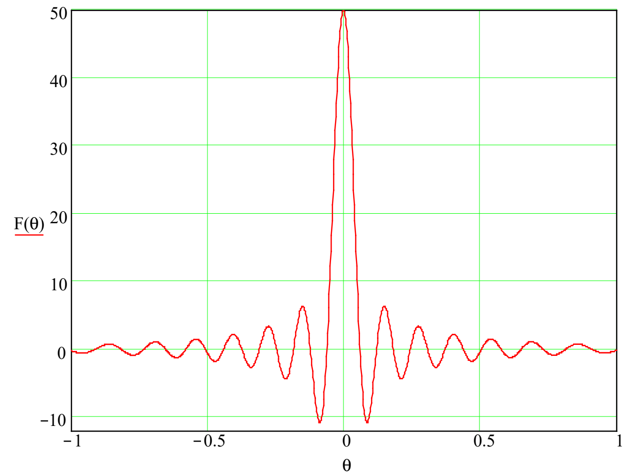
a



b

Fig. 7. Directivity diagram of the waveguide-slot antenna at a frequency of 4.0 GHz: *a* – in the polar coordinate system; *b* – in the Cartesian coordinate system

Fig. 8 shows the directional diagrams of the waveguide-slot antenna in the Cartesian coordinate system at frequencies of 4.5 GHz, 5.0 GHz, and 5.5 GHz. This is because for highly directional antennas, it is convenient to determine the width of the directional pattern and the level of the side lobes precisely in the Cartesian coordinate system.



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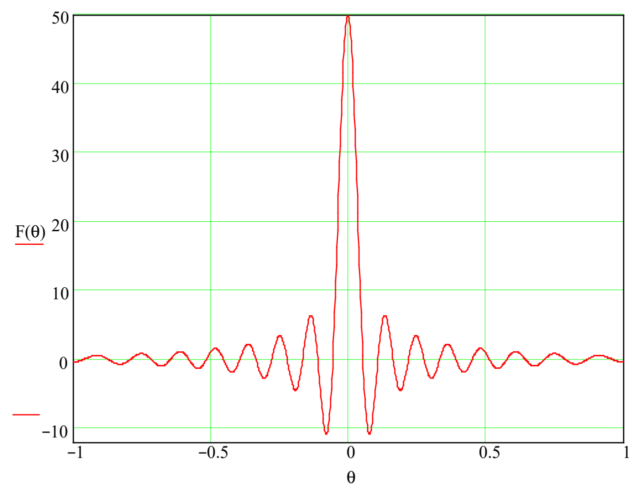

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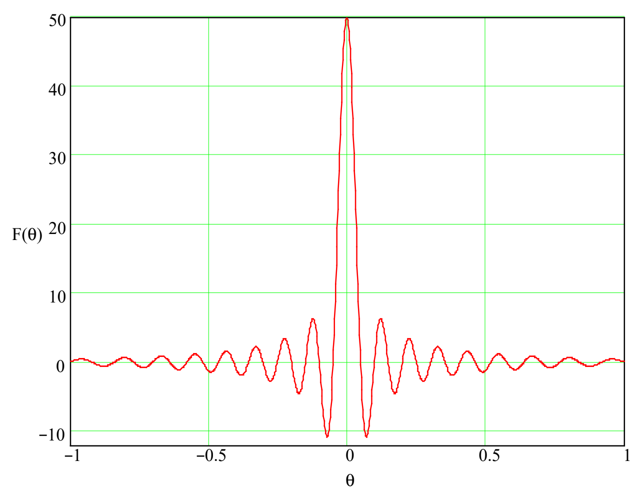

c

Fig. 8. Directivity diagram of the waveguide-slot antenna in the Cartesian coordinate system at frequencies: *a* – 4.5 GHz; *b* – 5.0 GHz; *c* – 5.5 GHz

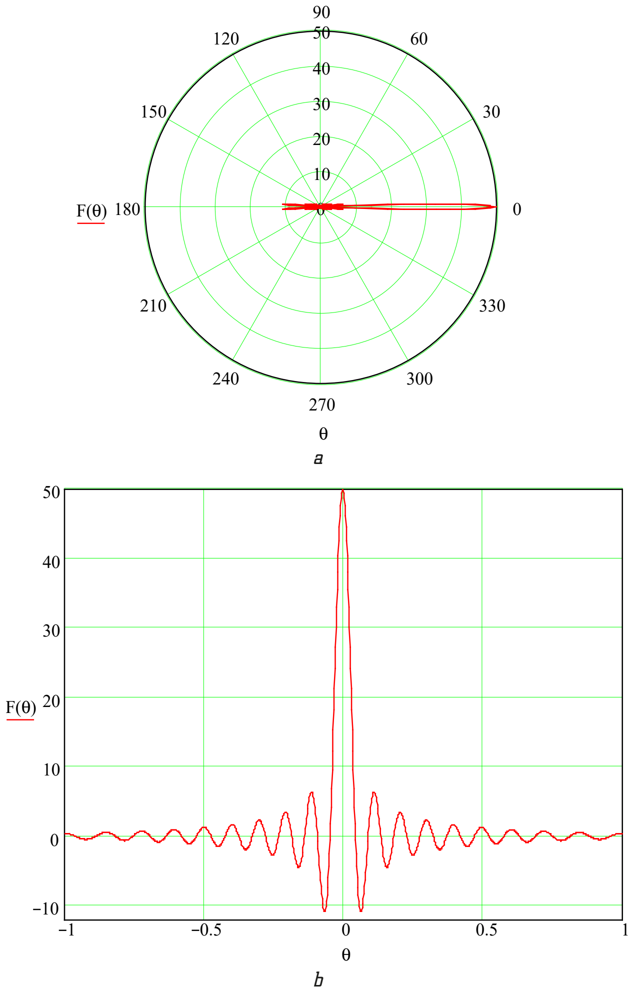

Fig. 9. Directivity diagram of a waveguide-slot antenna at a frequency of 6.0 GHz: *a* – in the polar coordinate system; *b* – in the Cartesian coordinate system

As can be seen from Fig. 7–9, the proposed resonant waveguide-slot antenna with in-phase excitation of the slots has a sharp amplitude pattern over the entire operating frequency range. Therefore, the emission and reception of electromagnetic waves by such an antenna will be carried out in a given direction in space. Thanks to this, the radiation energy will be concentrated in the specified spatial angular coordinates, which makes it possible to reduce the total radiation power, as well as the transmitter power. Reducing the power of the radio transmitter when the radio waves propagate over a given distance is an important technical result. This increases the energy efficiency of the radio frequency system, reduces the level of interference to neighboring radio stations and improves electromagnetic compatibility.

The main advantage of the proposed antenna is a wide range of operating frequencies, ease of manufacture and operation. Limitation of the application of the proposed resonant waveguide-slot antenna with in-phase excitation of the slots is a violation of the matching conditions at its input. In further research, it is planned to investigate the matching of the proposed antenna with the feeding feeder in a wide range of operating frequencies.

The main direction of further research is the development of a waveguide-slot antenna with circular polarization based on the proposed antenna. This will be done by cutting transverse slots at an angle of 90° to the existing ones. Then there will be cross-shaped slots on the surface of the wide wall of the waveguide. They will be excited by both transverse and longitudinal currents, which are in phase quadrature. This will correspond to the condition of excitation of the electromagnetic field of circular polarization. The study of the wave parameters of the waveguide-slot antenna with circular polarization, its amplitude directional pattern and polarization directional pattern is expected.

Another direction of the research of the waveguide-slot antenna based on the proposed antenna is the use of capacitive pins inside the rectangular waveguide to change the patterns of field lines of force during the passage of H_{10} wave. At the same time, the amplitudes and phases of the excitation currents of the emitted slots will be changed. This will enable electrical control of the parameters of the amplitude pattern of the waveguide-slot antenna.

4. Conclusions

In this work, the design of a compact microwave resonant waveguide-slot antenna with in-phase excitation of the slots for the frequency range of 4.0–6.0 GHz has been developed. The main electrical parameters of the waveguide-slot antenna are as follows: the frequency range according to the level of VSWR no more than 2.1 is 4.55–5.99 GHz, the coefficient of directional action in the working range is not less than 90, the width of the main lobe of the antenna directional diagram at the level of $2\theta_{0.5}$ is no more than 3.1°, the amplification factor in the operating frequency band is not less than 100, the efficiency is not less than 90 %, the maximum power of the generator signal is 10 kW. The antenna emits an electromagnetic wave with a linear polarization with an electric field strength vector perpendicular to the long side of the slot.

The proposed waveguide-slot antenna is easy to manufacture and operate. It has a low cost. The slot antenna has a fairly simple exciting device, which is convenient when tuning it to the operating frequency of the generator. The proposed waveguide-slot antenna in the operating frequency range has better wave properties and directional characteristics compared to horn antennas.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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