Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 5. С. 42–51
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 5, pp. 42–51

Electrodynamics, Microwave Engineering, Antennas

UDC 621.396.674 Original article

https://doi.org/10.32603/1993-8985-2019-22-5-42-51

Modeling and Practical Implementation of a Broadband Double-Ridged Horn Antenna with an Operating Range More Than an Octave and a High Level of Cross-Polarization Discrimination

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Abstract

Introduction. The resolution of the problem of radio polarimetry in multiposition microwave screening systems (MMSS) with aperture synthesis requires the use of antennas with a high level of cross-polarization discrimination (XPD) in a wide spatial angle. The radio images are reconstructed in MMSS at distances commensurate with the aperture of the antenna structures. Therefore, the value of the spatial angle, at which high XPD is required, can reach 30°. This leads to a new problem of creating an antenna configuration of the X and Ku band, the application of which in MMSS will resolve the problem of constructing a radio image of depolarized microwave radiation scattered on the human body in the form of hidden dangerous objects.

Aim. To develop a double-ridged receiving antenna for long-term operation in MMSS with an XPD level of 28 dB at a spatial angle of 30° and operating frequencies of 8...20 GHz.

Materials and methods. The requirements for the receiving antenna in MMSS were determined. Theoretical justifications were proposed for the choice of antenna design. Aperture synthesis was used to construct microwave images in MMSS. The stages and results of modelling broadband double-ridge antennas were presented using the CST Studio software broadly applied for three-dimensional electro-magnetic field modelling. The results of modelling pyramidal and conical double-ridged antennas, as well as those in circular and elliptical waveguides, were analyzed. The designed antenna was tested in an anechoic chamber. The measurement results were compared with those obtained during simulation.

Results. An elliptical double-ridged horn antenna with a VSWR of no more than 2 and cross-polarization discrimination in a spatial angle of 30° of no less than 28 dB for the frequency range that covers an octave was designed and constructed.

Conclusion. The developed antenna can be used in MMSS for the purpose of detecting the effect of micro-wave radiation depolarization as hidden dangerous objects on a human body. Such characteristics of the antenna as its high XPD value in a wide spatial angle will allow the future introduction of microwave polarimetry in MMSS.

Key words: double-ridged horn antenna, cross-polarisation discrimination, double-ridged elliptical antenna

For citation: Meshcheriakov V. V., Markova N. V., Iurmanov P. D. Modeling and Practical Implementation of a Broadband Double-Ridged Horn Antenna with an Operating Range More Than an Octave and a High Level of Cross-Polarization Discrimination. Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 5, pp. 42–51. doi: 10.32603/1993-8985-2019-22-5-42-51

Conflict of interest. The authors declare no conflict of interest.

Submitted 03.06.2019; accepted 29.09.2019; published online 29.11.2019

Электродинамика, микроволновая техника, антенны

Оригинальная статья

Моделирование и практическая реализация широкополосной двухгребневой рупорной антенны с шириной рабочей полосы более октавы и высоким уровнем кроссполяризационной развязки

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Аннотация

Введение. Для решения задачи радиополяриметрии в многопозиционных микроволновых досмотровых системах (ММДС) с апертурным синтезом необходимо использовать антенны с высоким уровнем кроссполяризационной развязки (КПР) в широком пространственном угле. Восстановление радиоизображений в ММДС происходит на дистанциях, соизмеримых с размерами апертуры антенных структур, поэтому значение пространственного угла, в котором необходимо выполнение требования высокой КПР, может достигать 30°. Таким образом, возникает новая задача создания антенной структуры X- и Ku-диапазонов, применение которой в ММДС позволило бы решить задачу построения радиоизображения деполяризованного микроволнового излучения, рассеянного скрытыми опасными объектами на теле человека.

Цель работы. Разработка приемной антенны жесткой конструкции для долговременной эксплуатации в ММДС с уровнем КПР 28 дБ при пространственном угле 30° и рабочих частотах 8... 20 ГГц.

Материалы и методы. Определены требования для приемной антенны в ММДС. Приведены теоретические обоснования для выбора конструкции антенны. В разработанной ММДС для построения микроволнового изображения используется апертурный синтез. Представлены этапы и результаты моделирования широкополосных двухгребневых антенн в программе трехмерного моделирования электромагнитного поля CST Studio. Рассмотрены результаты моделирования двухгребневых антенн: пирамидальной, конической, в круглом и эллиптическом волноводах. Произведено сравнение результатов измерения в безэховой камере для макета полученной антенны и результатов моделирования.

Результаты. Разработана и изготовлена двухгребневая эллиптическая антенна жесткой конструкции, с КСВН не более 2 и кроссполяризационной развязкой в пространственном угле 30° не менее 28 дБ в диапазоне частот, перекрывающем октаву.

Заключение. Антенна может быть использована в ММДС для детектирования эффекта деполяризации микроволнового излучения скрытыми опасными объектами на теле человека. Высокое значение КПР антенны в широком пространственном угле позволит в дальнейшем внедрить микроволновую поляриметрию в ММДС.

Ключевые слова: двухгребневая рупорная антенна, кроссполяризационная развязка, эллиптическая двухгребневая антенна

Для цитирования: Мещеряков В. В., Маркова Н. В., Юрманов П. Д. Моделирование и практическая реализация широкополосной двухгребневой рупорной антенны с шириной рабочей полосы более октавы и высоким уровнем кроссполяризационной развязки // Изв. вузов России. Радиоэлектроника. 2019. Т. 22, № 5. С. 42–51. doi: 10.32603/1993-8985-2019-22-5-42-51

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Статья поступила в редакцию 03.06.2019; принята к публикации после рецензирования 29.09.2019; опубликована онлайн 29.11.2019

Introduction. Currently, multiposition microwave screening systems (MMSSs) often use cross-polarisation methods to detect metal objects on the human body [1]. The MMSS shown in Fig. 1 at the place of operation is designed to continuously scan the flow of people for hidden explosive devices and automatic weapons on the human body and in backpacks. It uses the radio polarimetry method [2, 3], in

***Fig. 1*. Multiposition microwave screening system (MMSS) at the place of operation**

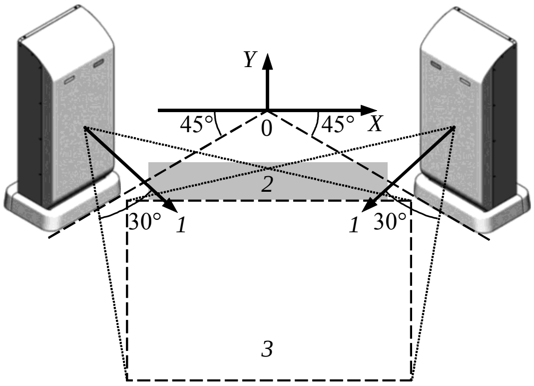


Fig. 2. MMSS location scheme:
1 – direction of the main lobes of the transmitting antennas in the array; *2* – zone of analysis of transmitted radiation; *3* – zone of analysis of reflected radiation

which broadband double-ridge antennas are used to obtain complete information about the scattered field from the target [4, 5]. The necessity of ensuring a high level of cross-polarisation discrimination (XPD) [6, 7] in the antenna structures used to obtain reliable results comprises a complex technical task for the frequency range having more than an octave of overlap [8, 9]. XPD (Cross Polar Discrimination – XPD [10]) refers to the minimum ratio of amplitudes of linear components of the electromagnetic field of main and cross-polarisation defined in the Ludwig-3 coordinate system [11] for a given spatial angle.

In the MMSS developed by the authors of this paper, aperture synthesis is used to build a microwave image. A significant limitation for the construction of radio images in cross-polarisation [1] is the unsatisfactory XPD value of the used antenna.

When carrying out the experiment described in [1], the minimum XPD value for the task of classifying dangerous objects on the human body is established: 5.0 in main polarisation and 0.2 in cross-polarisation, which is 28 dB. For the developed MMSS [12], it is necessary to maintain this value during the detection in the area of reflected radiation analysis (Fig. 2, *3*).

The multiposition system (Fig. 2) consists of two antenna arrays located at an angle of 45° to the *X*-axis. The inspection area includes the area for the analysis of past radiation *2* and the analysis area of reflected radiation *3* [13]. From the location and size of the reflected emission analysis area *3*, it follows that the spatial angle at which the specified XPD value is to be maintained must be at least 30°.

In the first MMSS version [12], Vivaldi printed antennas were used (Fig. 3); however, in the process of developing a system for detecting hidden objects by means of cross-polarisation scattering analysis, it was found that the XPD of these antennas failed to meet the requirements, since its level in the angle of 30º was only 4 dB at linearly polarised radiation. In a spatial angle of more than 30º at frequencies above 14 GHz, this antenna begins to dominate the cross-component, while the discrimination value drops to –10 dB. These parameters prohibit the use of this antenna to detect hidden dangerous objects described in [1].

Other Vivaldi antenna parameters in the operating range of 8…18 GHz:

– voltage standing wave ratio (VSWR) less than 1.8;

– the average value of the directional factor is 9 dBi;

– the width of the main lobe at the level of 3 dB in the dielectric substrate *x*0*z* (*E*-plane) 70…60º, in the cross-polarised plane *y*0*z* (*H*-plane) 85…30º are generally unsatisfactory for systems with aperture synthesis within the spatial angle of 30º.

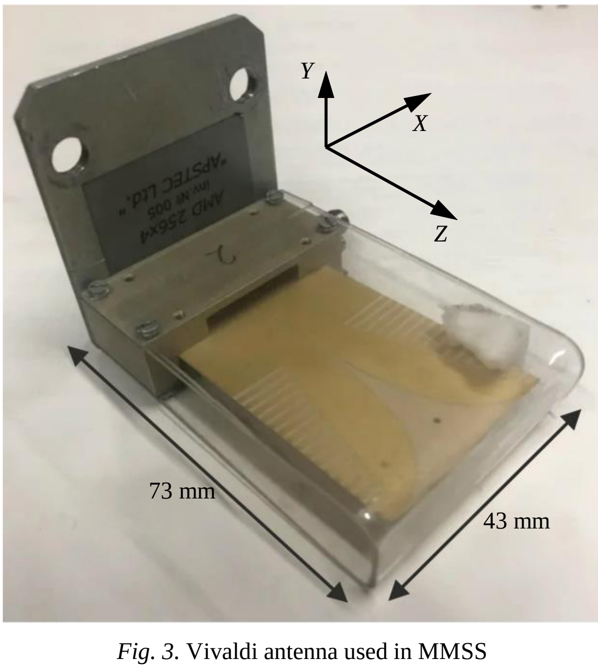


Fig. 3. Vivaldi antenna used in MMSS

The considered receiving antenna is additionally distinguished by its structural fragility and instability, as well as the insufficient repeatability of its electrodynamic parameters from sample to sample.

Work objective. To develop a receiving antenna with a high XPD level, operating in the X and Ku frequency ranges, by means of which to reliably solve the problem of restoration of radio images in the developed MMSS for microwave radiation, depolarised by the scattering of dangerous objects concealed on a human body.

In the developed receiving antenna, we set out to achieve the described parameters and eliminate the noted design flaws.

Research methods. Broadband structures developed on the basis of double-ridge antennas are well-known and widely used [4, 5]. In [4], the authors consider a double-ridge pyramidal horn powered by a coaxial cable; here the size of the structure and obtained electrodynamic parameters are given, but the XPD level is not indicated. In order to estimate this parameter, an electrodynamic simulation of the double-ridge pyramidal horn antenna was carried out using the CST STUDIO SUITE. Additionally, in order to determine XPD within the spatial angle of 30°, a double-ridge conical horn antenna and elliptical waveguide were modelled.

For antenna coordination, a double-ridge structure of exponential shape was used (Fig. 4), given by the expression:

$$d(z) = y_1 + (y_2 - y_1)\frac{1 - e^{\alpha z}}{1 - e^{\alpha h}}, \qquad (1)$$

where y_1, y_2 are the coordinates *y* of the beginning and end of the exponential part of the double-ridge structure; α – the exponent coefficient; *h* – horn length. Double-ridge structures of the considered antennas were fed by a coaxial cable with a wave resistance of 50 Ohm.

Let us estimate the aperture size for the pyramidal horn. According to [14], the H-shaped waveguide formed by two ridges in a rectangular waveguide has a lower critical frequency for the main wave type H_{10} in comparison with a rectangular waveguide. The wave type H_{10} is also the main wave type for the pyramidal horn. The exponential shape of the ridges ensures the matching of the H-shaped waveguide and the aperture of the rectangular pyramidal horn. Let us use the formula for the waveform in the pyramidal horn to estimate the relationship between the aperture size and the H_{10} directivity factor [15]:

$$D = 0.64\left(4\pi ab/\lambda^2\right),$$

where *a* and *b* are the transverse aperture dimensions.

According to [16], the width of the directional pattern (DP) in the *E*-plane *y*0*z* BW_E while in the *H*-plane, *x*0*z* is related to the size of the horn by the ratio:

$$a = 53\lambda/BW_E; \; b = 80\lambda/BW_H.$$

Then the required DF =10 dBi at an average frequency of 13 GHz for a 60° wide main lobe can be obtained for sizes $a = 22$ mm и $b = 30$ mm.

Due to the double-ridge structure inside the aperture at the antenna output (in the section ∅*c* Fig. 6), a wave of the type H_{11} is formed in the conical horn. Let us consider a simplified model of round waveguide radiation excited at the wave H_{11} [15] to determine the maximum size of the aperture required for the formation of the directivity factor (DF) equal to the DF of the previously-used Vivaldi antenna. When limiting the size of a round waveguide within

$$c/\lambda = 0.6...1.3 \qquad (2)$$

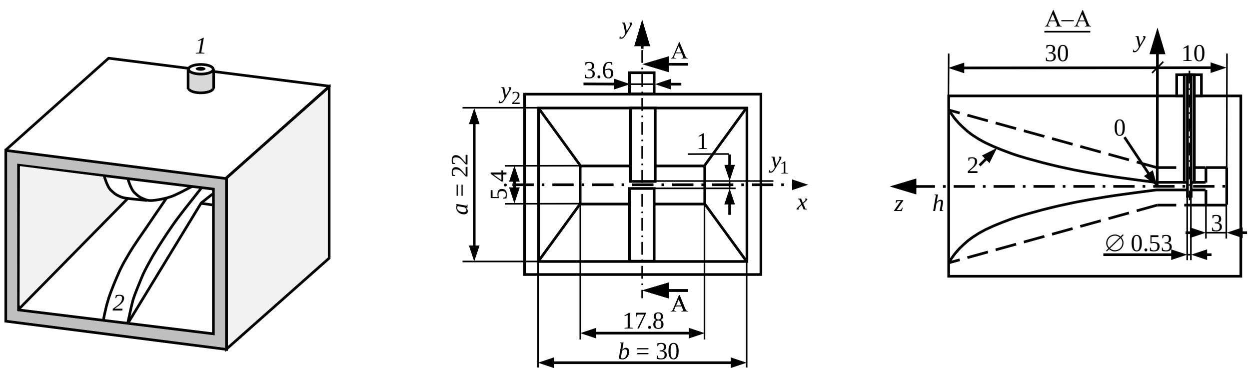


Fig. 4. Double-ridged pyramidal horn model:
1 – 50-ohm coaxial waveguide with fluoroplastic insulator; *2* – exponential metal arris

for DF, the following formula is valid:

$$D = (\pi c/\lambda)^2 \frac{\left(1+\sqrt{1-1.154\lambda/c}\right)^2}{4.775\sqrt{1-1.54\lambda/c}}, \qquad (3)$$

where c is the diameter of the horn aperture; λ is the wavelength of electromagnetic radiation. Thus, for the average frequency range of 13 GHz and DF =10 dBi, it is necessary to have $c = 25$ mm.

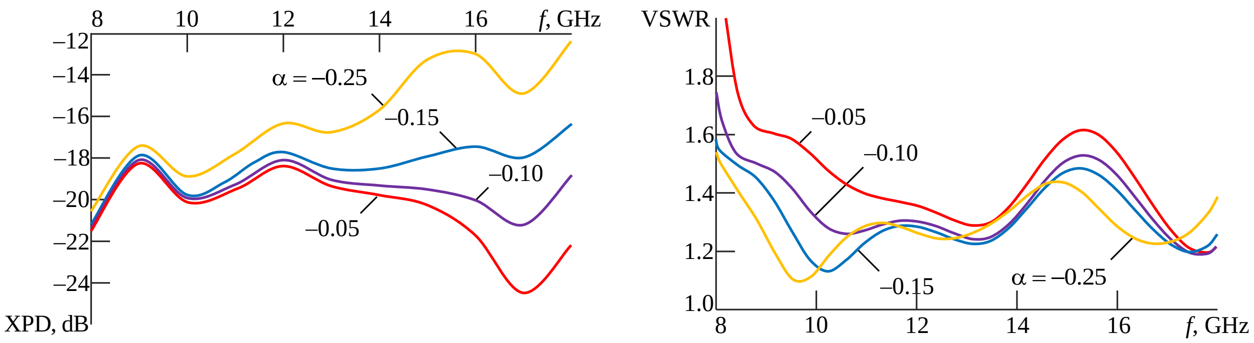
Modelling. Fig. 4 presents the analysed model of the double-ridge pyramidal horn antenna. The shape of the ridge *2* is defined (1), the dimensions $a = 22$ mm and $b = 30$ mm are selected to obtain the required DF according to (3).

For this model, the frequency dependencies of VSWR (Fig. 5, *b*) and XPD within the spatial angle of 30° were obtained (Fig. 5, *a*) for different values of the α coefficient. The above graphs show that the coefficient α significantly influences the XPD level, while VSWR for all the above α values does not exceed 2. The optimal value for this task is the value $\alpha = -0.1$, however, the obtained XPD value 18 dB min does not meet the stated requirement of 28 dB, while production errors will further degrade this parameter.

Therefore, we decided to study the conical horn. Fig. 6 shows the model of the conical double-ridge horn antenna under study, consisting of two parts: the horn itself with an aperture of the diameter c and a circular waveguide of the radius 8 mm. The ridge structure has an exponential edge shape $d(z)$, given by (1). The ridges are beveled on the short-circuit wall side for better coordination.

According to the limits set (3), the values of VSWR and XPD within the spatial angle of 30° for the diameter of the horn 16, 20, 25 and 30 mm are calculated (Fig. 7).

According to the results of modelling, the model of the double-ridge conical antenna has a VSWR no greater than 2 in the upper frequency range and XPD no less than 25 dB in the frequency range with overlapping in the range equal to 1.8. The DF at 13 GHz for the aperture $c = 25$ мм corresponds to a value of 10 dBi calculated per (3). At the same time, the XPD frequency dependency (Fig. 7, *a*) shows that with an aperture diameter of more than 20 mm, it deteriorates significantly. This is due to the out-phase of the conical horn: for larger aperture diameters, the phase distribution in the antenna aperture will be different from the uniform, i.e. non-incoherent, distribution. Based on the results shown in Fig. 7, the required level of XPD within the spatial angle of 30° is



a *b*

Fig. 5. Frequency dependences of the parameters of the pyramidal horn:
a – XPD; *b* – VSWR in a spatial angle of 30°

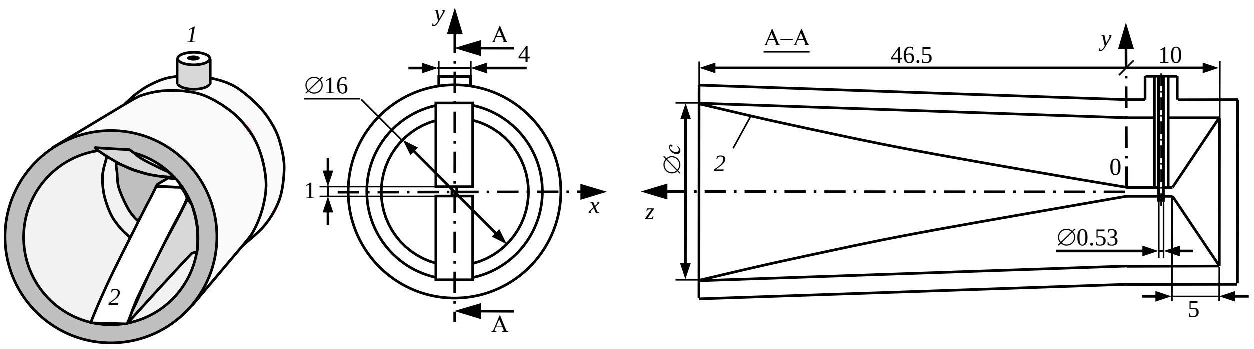


Fig. 6. Double-ridged cone model:
1 – 50-Ohm coaxial waveguide with fluoroplastic insulator; *2* – exponential metal ridge

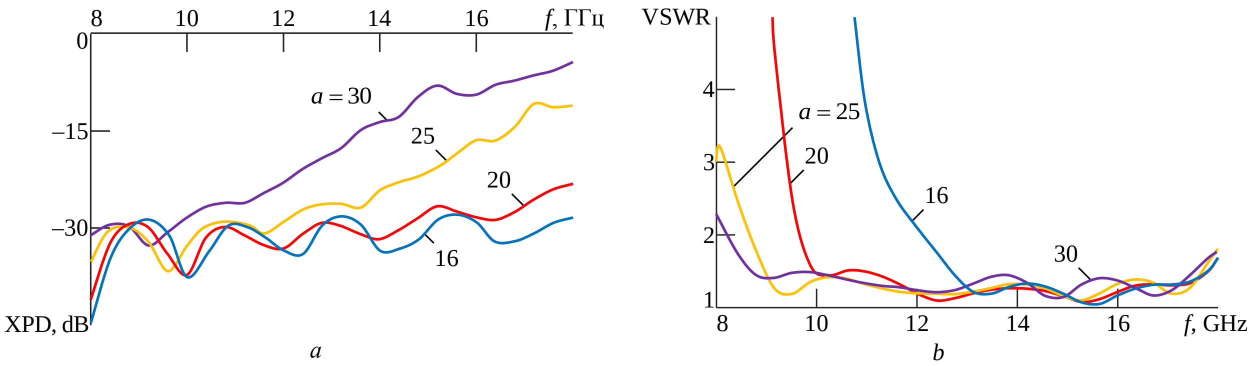


Fig. 7. Frequency dependences of the parameters of the conic horn: *a* – XPD in a spatial angle of 30°; *b* – VSWR

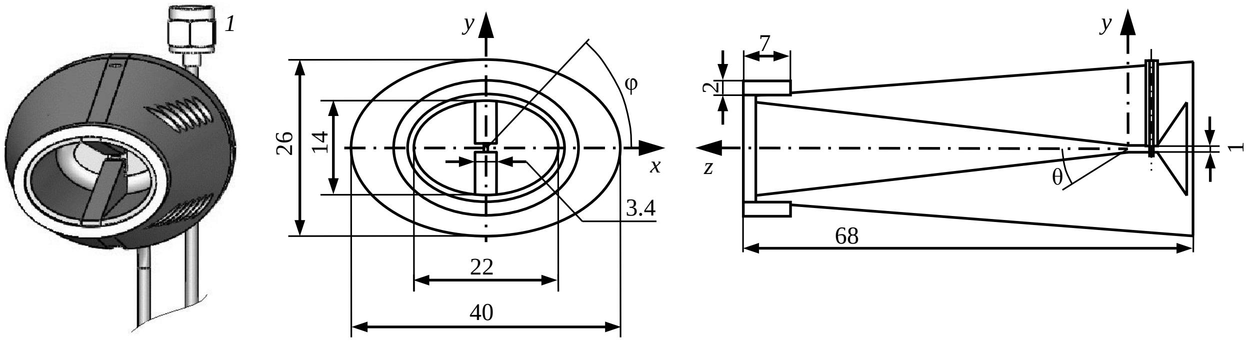


Fig. 8. Model of an elliptical double-ridged antenna: *1* – 50-Ohm coaxial waveguide with fluoroplastic insulator

achieved by reducing the aperture size to 16 mm. It should be noted that it is impossible for the aperture to approach the size of the round waveguide because, in this case, the minimum operating frequency of the antenna would increase unacceptably.

The required electrodynamic and design parameters can also be obtained in a double-ridge antenna developed based on an elliptical section waveguide. The elliptical shape of the waveguide eliminates the degeneration of the wave type H_{11}, which is characteristic of a circular waveguide, as well as providing fixation of the polarisation plane [17].

We assumed that the location of the ridges along the small axis of the elliptical waveguide would improve the XPD value within the spatial angle of 30°. Fig. 8 shows a 3D model of an elliptical double-ridge antenna (*1* – 50-Ohm coaxial cable with a fluoroplastic insulator, terminated with SMA connector).

Figs. 9, 10 show the frequency dependencies of VSWR, XPD within the spatial angle of 30°, DP width in *E*- and *H*-plane, BW_E and BW_H and DF. These results were obtained at the following elliptical antenna sizes:

– transverse dimensions of an elliptical waveguide in the aperture plane $a_{\text{el}} \times b_{\text{el}} = 11 \times 7$ mm^2, where a_{el} and b_{el} are the major and minor semi-axes of an ellipse, respectively;

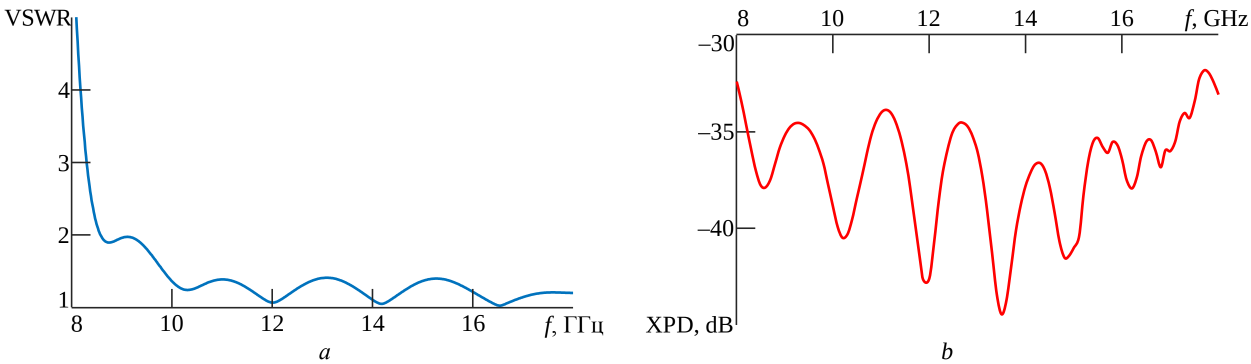


Fig. 9. Frequency dependencies of the parameters of the elliptical double-ridge antenna: *a* – VSWR; *b* – XPD in a spatial angle of 30°

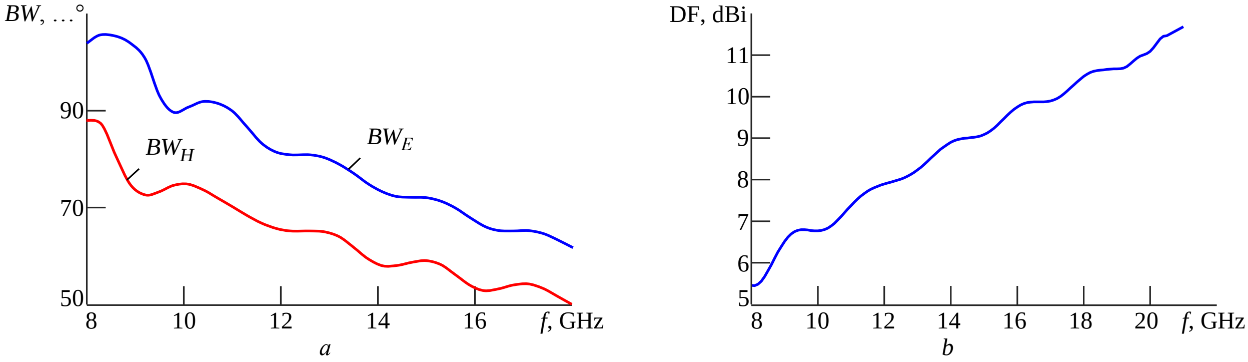


Fig. 10. Frequency dependences of the parameters of the an elliptical double-rib antenna:
a – radiating pattern by level –3 dB in *E*-plane (blue line) and *H*-plane (red line); *b* – DF

– ridge thickness 3.4 mm;

– slit width at the power source 1 mm;

– antenna length 68 mm.

The conical external shape of the antenna reduces the reception of foreign radiation by its aperture compared to a cylindrical antenna. Increasing the size on the right end of the antenna added rigidity and stability to the entire structure.

In the antenna aperture plane, there is a small fluoroplastic ring, which, according to the results of the simulation, significantly reduces the level of cross-polarised radiation in the lower part of the frequency range.

Modelling of the elliptical double-ridge antenna gave the following parameters:

– VSWR ≤ 2;

– XPD in a spatial angle of 30° not less than 30 dB in the overlapping frequency range 2.2;

– the width of the main lobe and DF meet the requirements to ensure the reception of the signal from the target in the analysis area of the reflected microwave radiation (see Figs. 2, *3*).

Results. Fig. 11, *a* shows the layout of the manufactured double-ridge elliptical antenna. The results of the study of its electrodynamic parameters in the plane set by the angle φ (see Fig. 8) are shown in Fig. 12. XPD distribution is based on the deviation angle θ from the antenna axis symmetry (see Fig. 8).

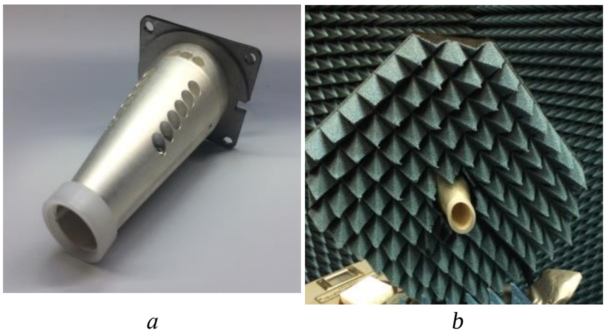


Fig. 11. Elliptical double-beam antenna:
a – model; *б* – installation
in the ECCOSORB VHP-2-NRL absorber array

In order to preserve the XPD level during the formation of an ensemble of receiving elliptical double-ridge antennas, it is necessary to use an absorbing material, for example, ECCOSORB VHP-2-NRL. Fig. 11, *b* shows a photo of the antenna in the ECCOSORB VHP-2 absorber array in the anechoic chamber in which measurements were made [18]. The analysis of the results of experimental studies of the developed and manufactured elliptical double-

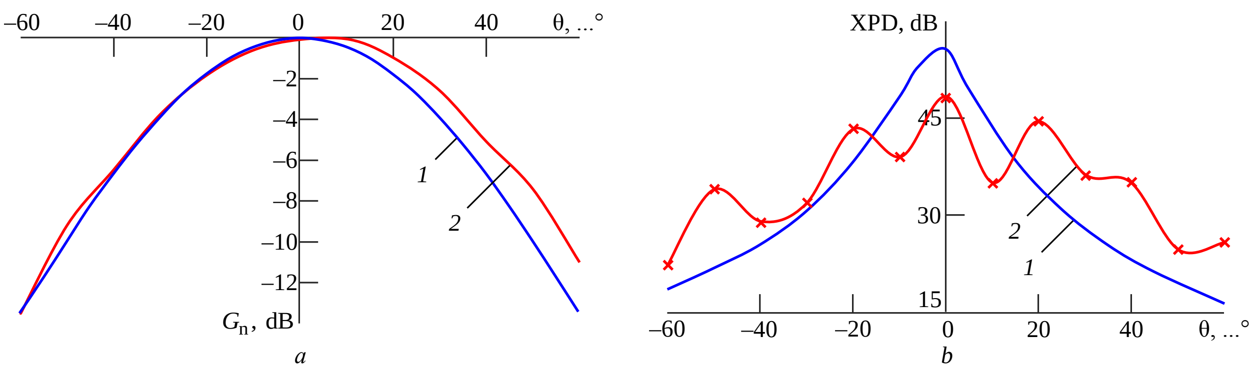


Fig. 12. Theoretical *1* and experimental *2* dependences of the parameters of an elliptical double-ridge antenna
at a frequency of 18 GHz in the plane $\varphi = 45°$: *a* – normalized to the maximum gain ratio; *b* – XPD

ridge antenna shows that the experimental data and the results of modelling are well correlated. The XPD value of the manufactured antenna at a frequency of 18 GHz within the spatial angle of 30° is better than 30 dB; with a decrease in the frequency, the level of discrimination increases. This is entirely consistent with the results of the simulation that allows the use of antennas in MMSSs.

Conclusion. A double-ridge elliptical antenna was developed and manufactured, with $\text{VSWR} \le 2$ and XPD in a spatial angle of 30° not less than 28 dB in the frequency range overlapping octave. The antenna can be used in MMSSs to detect the effect of microwave radiation depolarisation by hidden dangerous objects on the human body. Structurally, the double-ridge antenna is assembled in three parts – the upper and lower halves of the elliptical waveguide and the double-ridge plate, which are joined together in one piece with screws. Although this design meets the tight design tolerances set by the simulation, it requires high production standards.

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