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Article

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STUDY OF THE RADIATION PATTERN OF A RECTANGULAR HORN ANTENNA IN THE OPERATION OF MULTIMODE PROPAGATION OF ELECTROMAGNETIC WAVES

The object of research in the work is the process of radiation of electromagnetic waves and the directional properties of a rectangular horn antenna in a multimode operation. The existing problem is that in practice when developing and researching horn antennas, only the single-mode mode of their operation is taken into account. The fundamental mode of the rectangular waveguide that feeds this horn antenna is chosen as the base mode of the emitted electromagnetic wave. Radiation of higher types of electromagnetic waves is not taken into account.

To take into account the impact of higher types of electromagnetic waves on the directional properties of a rectangular horn antenna, it is proposed to investigate a multimode mode consisting of three types of magnetic waves H_{10}, H_{20}, and H_{30}. Horn antennas have high-quality wide-range properties and make it possible to obtain a maximum frequency coverage ratio of 1.5–1.8. In this paper, the directional properties of a rectangular horn antenna are determined by the example of calculating and modeling normalized radiation patterns of a standard horn-type for a wide frequency range with an average frequency of 12 GHz and a frequency overlap factor of 1.67.

It has been established that when emitting three higher types of waves, it is possible to simultaneously improve the characteristics and directional properties of a horn antenna by changing the amplitude of each component of the constituent waves of electromagnetic radiation. The work aimed to study the normalized radiation patterns of a rectangular horn antenna to improve its directional properties. It was found that with increasing frequency, starting from the middle frequency of the operating frequency range, the radiation pattern of a rectangular horn antenna expanded. That is, the opening angle increased in the direction of the main radiation, with a decrease in the radiation amplitude, the level of the side and rear lobes increased, which leads to a deterioration in the characteristics of the horn antenna. For the selected geometric dimensions of the horn antenna in the frequency range of 12–12.5 GHz in the multimode mode, it was possible to provide almost the same beam width in the horizontal and vertical planes at the level of 13.2–13.6°.

Keywords: *horn antenna, rectangular horn, frequency range, electromagnetic wave, multimode, single-mode.*

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1. Introduction

Waveguide radiators and horn antennas are a common type of microwave antenna [1]. They are used as separate antennas, as well as radiating elements of other antennas (reflex, lens) [2].

These antennas are widely used in the ranges of centimeter and millimeter wavelengths of electromagnetic waves [3].

Horn antennas make it possible to form radiation patterns from 100–140° wide (when opening a special geometric shape) to 10–20° in pyramidal horns. The possibility of further narrowing the horn's directivity pattern is limited by the need for a sharp increase in its geometric dimensions [4].

The main advantages of horn antennas are [5, 6]:

1. Wide band of operating frequencies. Horn antennas have approximately one and a half overlap in range. The possibility of changing the operating frequency to an even greater extent is limited by the complexity of the excitation and propagation of higher types of electromagnetic waves in the feeders that feed them.
2. High efficiency (in practice 96–98 %).
3. Large limiting power of the microwave (extremely high frequencies) signal.
4. Horn antennas are fairly easy to manufacture.

The main disadvantages of horn antennas are [7, 8]:

1. Bulky design.
2. The complexity of the formation of narrow radiation patterns.
3. Difficulties in adjusting the amplitude-phase distribution of the field in the opening. This limits the ability to reduce the level of side lobes and create specially shaped radiation patterns.

There are two ways to solve the problem of reducing the length of the horn. The first is to use a multi-horn antenna. The large size of the opening of the antenna is divided into n parts. Then the length of each horn can be reduced by a factor of n^2 compared to the length of a single-horn antenna. The horns are placed along a straight line in the same plane and connected so that the length of the wave path from the common waveguide to each of the horns is the same. This achieves the in-phase excitation of the horns [9].

The second way to reduce the length of the horn is based on the use of special devices that correct phase distortions in the opening of the horn. They artificially equalize the length of the path that the electromagnetic wave passes from the mouth of the horn to all opening points. Or, various types of lenses are arranged in the opening of the horn. These lenses align the phase front of the wave. Or they use metamaterials inside the horn [10].

IT technologies are widely used in modern tools and methods for automatic measurement of antenna patterns [11]. Conventionally, they can be divided into software and hardware-software implementations using IT technologies. Among the software methods for studying the processes of radio wave propagation, one should note such multitasking software packages as Ansys Electronics, CST Microwave Studio, Altair Feko, COMSOL Multiphysics, EMCoS Studio and others. These software packages are designed to simulate a wide range of physical and technical problems associated with the excitation and propagation of radio waves. However, such software packages require powerful computing resources and are expensive. Another disadvantage is the limited possibility of built-in application for automatic meters of antenna parameters.

Modern automatic meters of microwave parameters of antennas of the world's leading manufacturers using IT technologies are known. Among them, PNA Network Analyzer Family and Agilent PNA Series Microwave Network Analyzers should be highlighted. Such automatic meters of microwave antennas have wide integration with information devices and developed software capabilities. As part of their composition, they have powerful computing tools to ensure high measurement accuracy and high measurement speed. Their main disadvantage is their high cost. Therefore, it is not financially feasible to use them to solve a separate technical problem.

The vast majority of scientific studies of the directional properties of horn antennas have been carried out for the single-mode mode. Little attention has been paid to the study of the parameters and characteristics of horn antennas in the multimode regime. Therefore, *the object of research* in the work is the process of radiation of electromagnetic waves and the directional properties of a rectangular horn antenna in a multimode operation.

The aim of this research is to study the directional properties of a rectangular horn antenna in the multimode propagation of electromagnetic waves.

2. Research methodology

The amplitude radiation pattern of the antenna is an important characteristic of modern antennas for information and communication systems. The antenna pattern is the dependence of the intensity of the electromagnetic field emitted by the antenna in the far zone on the angles θ and φ at the same distance from the observation point to the origin. The physical content of the amplitude radiation pattern of the antenna is that it characterizes the ability of the antenna to concentrate electromagnetic energy in the desired sector of space [12]. In this paper, the amplitude radiation pattern of the antenna was calculated at three frequencies of the operating range. Namely, at the lower, middle and upper frequencies of the range. This is done in order to find out the band properties of a rectangular horn antenna.

When considering the processes of directed propagation of electromagnetic waves, one should introduce a coordinate system. When studying the directed propagation of electromagnetic waves, a spherical coordinate system is used. For the convenience of interpreting the results of the directional propagation of electromagnetic waves, the spherical coordinate system is combined with the Descartes coordinate system. In this case, the Cartesian coordinate system is oriented in such a way that the z-axis is directed in the direction of the main propagation of electromagnetic waves. Then the transverse plane will be the plane XOY. The view of the horn antenna and the coordinate system for calculating the amplitude radiation pattern are shown in Fig. 1.

The calculation of the normalized amplitude radiation pattern in the horizontal and vertical planes in the single-mode mode of a rectangular horn antenna is performed according to the following formulas [13]:

– in the plane H:

$$F_H(\varphi)=\frac{1+\cos\varphi}{2}\cdot\frac{\cos\left(\frac{\pi a_p}{\lambda}\cdot\sin\varphi\right)}{1-\left(\frac{2a_p}{\lambda}\sin\varphi\right)^2}, \qquad (1)$$

– in the plane E:

$$F(\theta)=\frac{1+\cos\theta}{2}\cdot\frac{\cos\left(\frac{\pi b_p}{\lambda}\cdot\sin\theta\right)}{\frac{\pi b_p}{\lambda}\sin\theta}, \qquad (2)$$

where a_p and b_p are the dimensions of the wide and narrow sides of the opening of a rectangular horn (Fig. 1); λ is the length of the electromagnetic wave.

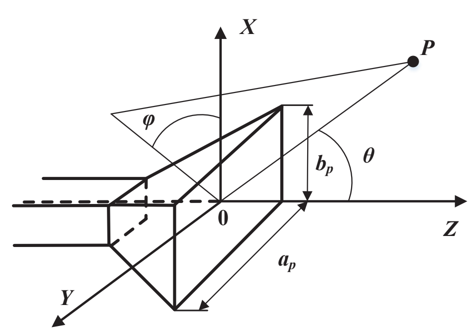


Fig. 1. Coordinate system when calculating the amplitude radiation pattern of a rectangular horn antenna

Let's make calculations for three types of magnetic waves (H_{10}, H_{20}, H_{30}). Let's study the dependence of the radiation pattern on the amplitude during the simultaneous emission of these waves [14]. The calculation of the normalized partial radiation pattern of a rectangular horn antenna is made according to formulas (3), (4) for each wave separately [13]:

– for the plane H:

$$F_H(\theta)=B\frac{\cos\left(\frac{mka_p}{2}\cdot\sin\theta\right)}{1-\left(\frac{2ma_p}{\lambda}\sin\theta\right)^2}, \qquad (3)$$

– for the plane E:

$$F\ (\theta)=A\frac{\sin\left(\frac{kb_p}{2}\cdot\sin\theta\right)}{\frac{kb_p}{\lambda}\sin\theta}, \qquad (4)$$

where B and A – the amplitude values; m – the index of the corresponding type of magnetic wave (1, 2 or 3); $k=2\pi/\lambda$ – the constant propagation of an electromagnetic wave in free space. The total radiation pattern of a rectangular horn antenna was determined by the formula:

$$F(\theta)=F_{H_{10}}(\theta)+F_{H_{20}}(\theta)+F_{H_{30}}(\theta). \qquad (5)$$

In this work, let's study the radiation patterns of a straight antenna for the three lower types of electromagnetic waves H_{10}, H_{20} and H_{30}. The total radiation pattern of a rectangular horn antenna is determined by formula (5).

3. Research results and discussion

In this paper, the directional properties of a rectangular horn antenna have been studied with the following geometric dimensions:

– wide opening wall of the horn $a_p=147$ mm;
– narrow wall opening of the horn $b_p=98$ mm;
– length of the horn in the plane $H{\cdot}R_H=293$ mm;
– horn length in plane $E{\cdot}R_E=286$ mm;
– length of the rectangular horn (distance from the opening of the rectangular waveguide to the mouth of the horn) $h=256.4$ mm.

In the plane E, the radiation pattern will be unchanged; therefore, in this plane, it is not investigated, but go to the plane H. In the plane H, for the H_{10} wave, let's take the amplitude constant, that is, $B=1$, and for the H_{20} and H_{30} waves, let's change the amplitude. Fig. 2–5 show the normalized total amplitude radiation patterns of a horn antenna in the plane H for a wavelength of 24.5 mm, calculated using relations (3) and (5).

Usually, electrodynamics problems of radio wave propagation, which are described by differential equations, are solved in computer technology using the Finite Element Method (FEM) [15]. Modern software packages for studying the processes of radio wave propagation use other computational methods to solve electrodynamics problems. The most widespread are two of them: the Finite-Difference Time-Domain method (FDTD) and the Finite-Difference Frequency-Domain method (FDFD) [15, 16].

For computer simulation, the EMC Studio software package was used. This program was chosen because it uses the latest advances in IT technology. This application allows analyzing the operation of a horn antenna, visually analyzing the spatial radiation patterns. The EMC Studio software package is widely used to model various types of antennas.

$$F(\theta) := \frac{\left|\frac{\sin\left(0.209\frac{61.975\sin(\theta)}{2}\right)}{\left(0.209\frac{61.975\sin(\theta)}{2}\right)}\right| + \left|\frac{\sin\left(0.209\frac{61.975\sin(\theta)}{2}\right)}{\left(0.209\frac{61.975\sin(\theta)}{2}\right)}\right| + \left|\frac{\sin\left(0.209\frac{61.975\sin(\theta)}{2}\right)}{\left(0.209\frac{61.975\sin(\theta)}{2}\right)}\right|}{3}$$

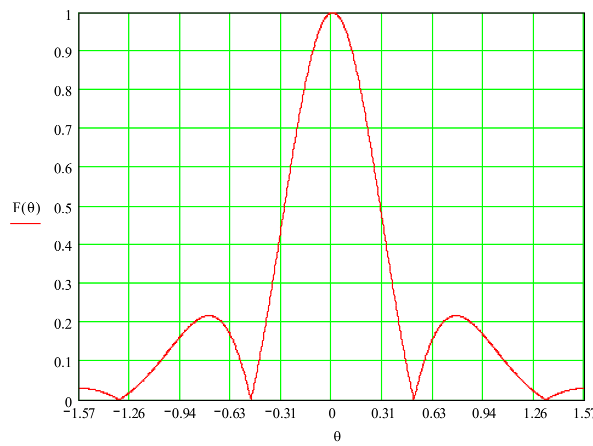


Fig. 2. Amplitude radiation pattern of a rectangular horn antenna in plane E at $A=1$

$$f(\theta) := \frac{\left|\frac{\cos\left(\frac{0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{71.25\sin(\theta)}{30}\right)^2}\right| + \left|\frac{\cos\left(\frac{2\cdot0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{2\cdot71.25\sin(\theta)}{30}\right)^2}\right| + \left|\frac{\cos\left(\frac{3\cdot0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{3\cdot71.25\sin(\theta)}{30}\right)^2}\right|}{3}$$

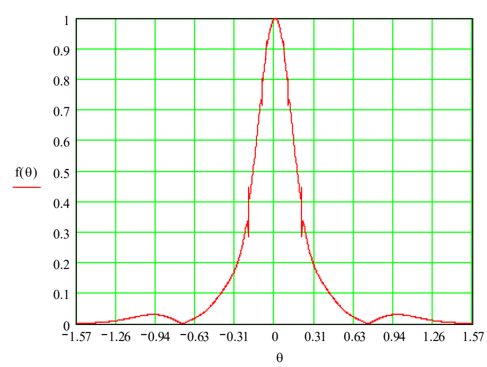


Fig. 3. Amplitude radiation pattern of a rectangular horn antenna in the plane H at $B=1$

$$F(\theta) := \frac{\left|\frac{\cos\left(\frac{0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{71.25\sin(\theta)}{30}\right)^2}\right| + \left|\frac{0.5\cos\left(\frac{2\cdot0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{2\cdot71.25\sin(\theta)}{30}\right)^2}\right| + \left|\frac{0.5\cos\left(\frac{3\cdot0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{3\cdot71.25\sin(\theta)}{30}\right)^2}\right|}{2}$$

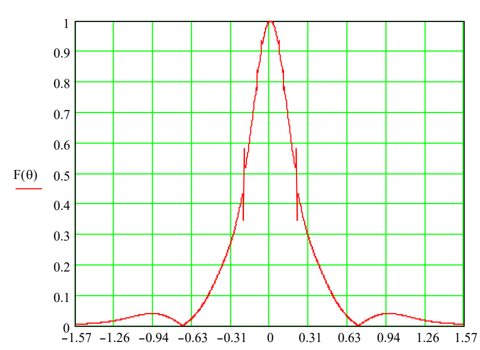


Fig. 4. Amplitude radiation pattern of a rectangular horn antenna in the plane H at $B=0.5$

$$F(\theta) := \frac{\left| \left[\frac{\cos\left(\frac{0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{71.25\sin(\theta)}{30}\right)^2} \right] + \left[\frac{0.2\cos\left(\frac{2\cdot 0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{2\cdot 71.25\sin(\theta)}{30}\right)^2} \right] + \left[\frac{0.2\cos\left(\frac{3\cdot 0.20971.25\sin(\theta)}{2}\right)}{1-\left(2\cdot\frac{3\cdot 71.25\sin(\theta)}{30}\right)^2} \right] \right|}{1.4}$$

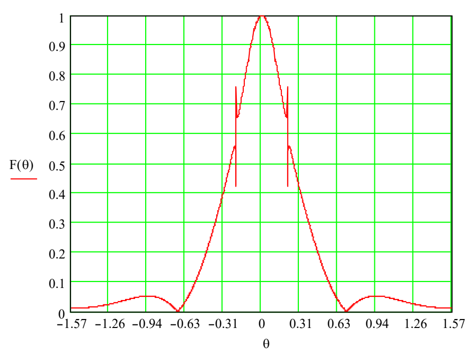


Fig. 5. Amplitude radiation pattern of a rectangular horn antenna in the plane H at $B=0.2$

A 3D model of the studied antenna was created in the EMC Studio software package. The source is set; the desired frequency band is set. In this study, the studied horn antenna is modeled in the frequency range of 9–15 GHz.

A new project called «horn antenna» was created, the walls of the horn were set to metal (Fig. 6).

The plane crossing this horn is used as an auxiliary one to create the correct symmetrical shape of the horn (Fig. 6). The results of modeling the spatial amplitude radiation pattern are shown in Fig. 7.

In Fig. 7 the horn is not visible because the image of the levels of electromagnetic radiation is covered. The normalized radiation patterns in the plane H of a rectangular horn antenna operating in multimode for different frequencies are shown in Fig. 8.

The spatial radiation patterns of a rectangular horn antenna, obtained as a result of modeling in EMC Studio, are shown in Fig. 9.

Based on the results of computer simulation, it can be concluded that a rectangular horn antenna ensures the constancy of sharply directed properties in a narrow band of operating frequencies of 12.0–12.5 GHz. This is due to the fact that the geometric dimensions of the horn play a significant role in wave processes when the length of the waves that feed it changes.

A modern direction in the design of radio modules is the use of Substrate integrated waveguide (SIW) technology [4]. A further development of this research is the creation of rectangular horn antennas of millimeter-wave electromagnetic waves using 3D printing methods. This will significantly reduce the blocks and modules of electronic equipment. 3D printed rectangular horn antennas will work in multimode. Therefore, the results of studying the directional properties of a rectangular horn antenna obtained in this work will be used in the future.

The method proposed in the paper for studying the radiation pattern of a rectangular horn antenna in the mode of multimode propagation of electromagnetic waves will form the basis for the creation of an automatic measuring tool with built-in software. The facility will make automatic great-circle measurements of mm wave horn antennas. The proposed simplified mathematical model (1)–(5) will be used in the program of the digital part of the automatic means for monitoring the measurement results.

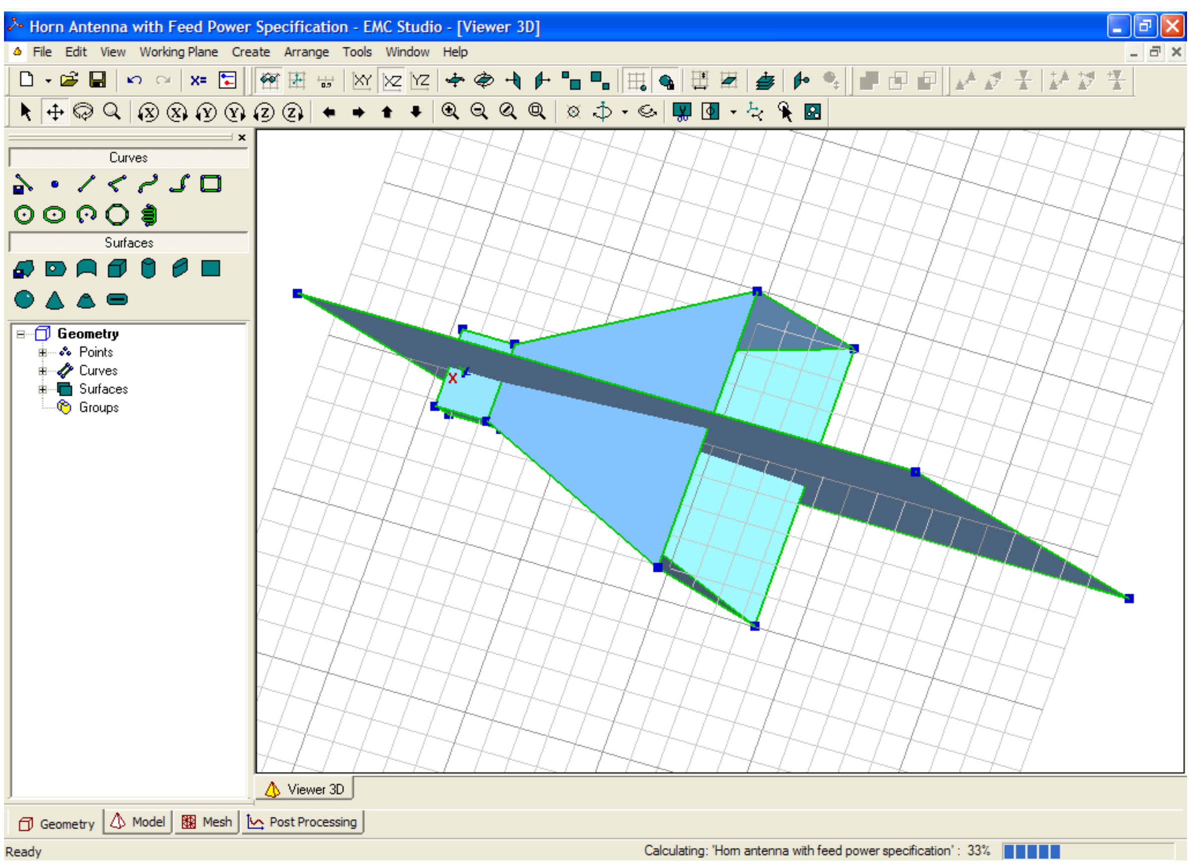


Fig. 6. General view of the rectangular horn antenna model in EMC Studio

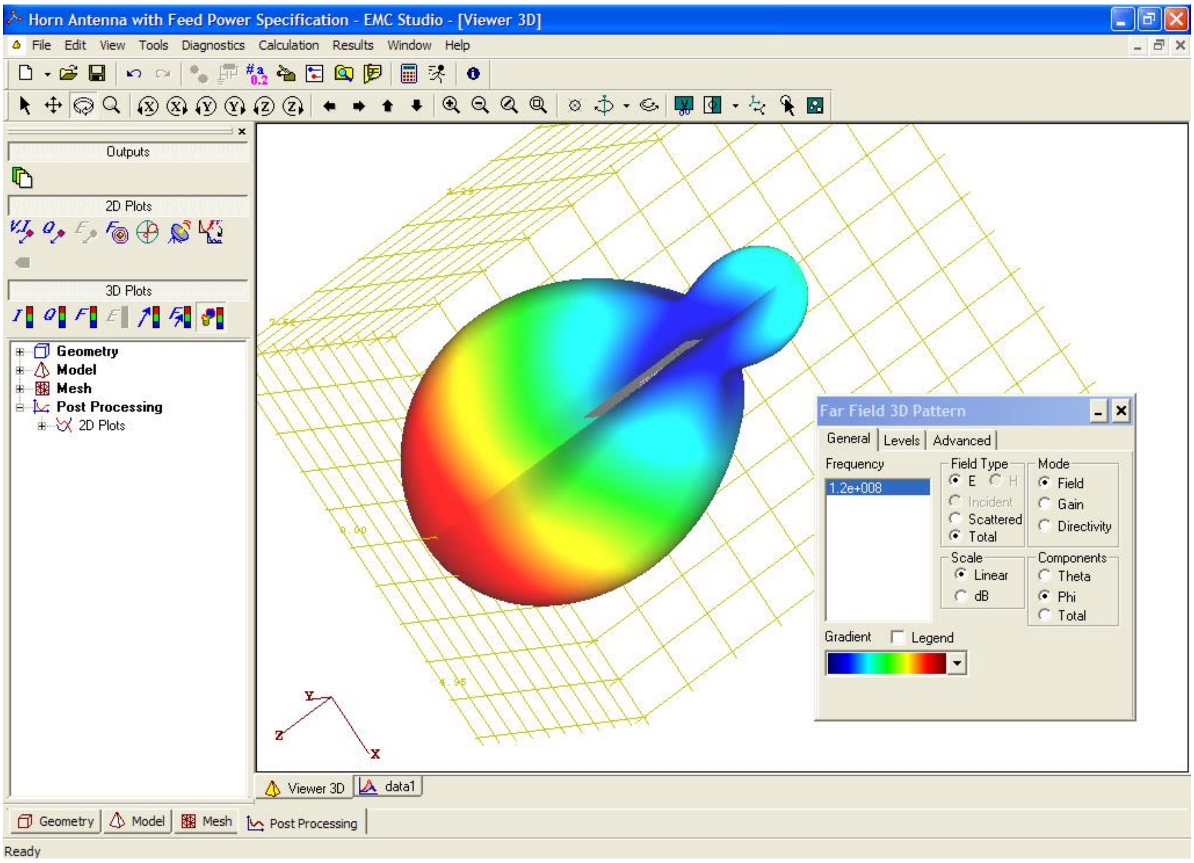
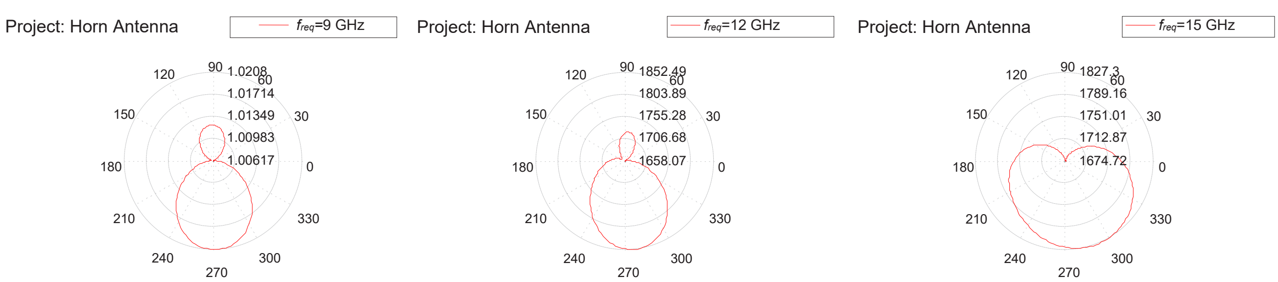
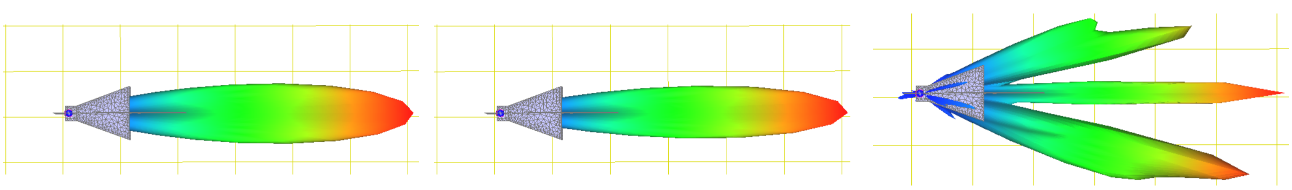


Fig. 7. Amplitude radiation pattern of a rectangular horn antenna in EMC Studio at an average frequency of 12 GHz



a *b* *c*

Fig. 8. The normalized amplitude radiation patterns of a rectangular horn antenna studied in EMC Studio in the *H* plane at the frequency: *a* – 9 GHz; *b* – 12 GHz; *c* – 15 GHz



a *b* *c*

Fig. 9. Spatial amplitude radiation patterns of a rectangular horn antenna studied in EMC Studio at a frequency of: *a* – 9 GHz; *b* – 12 GHz; *c* – 15 GHz

4. Conclusions

In this research, a study was made of the directional properties of a rectangular horn antenna. Its advantage is that it has a sufficiently high directivity, high efficiency, and, accordingly, a large gain. This antenna has a fairly simple design that does not require high-precision and complex calculations. The width of the radiation pattern $2\theta_{0.5}=13.20°$ and $2_{\varphi 0.5}=13.60°$ in a narrow frequency range of 12–12.5 GHz was ensured to be constant. According to calculations, the width of the radiation pattern in the frequency range of 9–15 GHz varies within the following limits: $2\theta_{0.5}=11–18°$ and $2_{\varphi 0.5}=12–20°$.

In such antennas, optimal spatial patterns can be implemented, since the field distribution in the opening can be chosen over a wide range by changing the coupling of the radiators with the waveguide. Based on the results of studying the characteristics of a horn antenna during the propagation of three types of waves simultaneously, it was found that the characteristics of a horn antenna can be improved by changing the amplitude of the radiation frequency. The width of the radiation pattern of a rectangular horn antenna increases with a decrease in the radiation amplitude and an increase in frequency, the level of the side and rear lobes increases, which leads to a deterioration in the characteristics of the horn antenna.

The wide frequency range, high directivity and simple design of rectangular horn antennas are the main advantages. The paper found that it is advisable to use a rectangular horn antenna at frequencies above the frequency at which it is optimal.

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