

ON BASE FREQUENCY OF THE SYMMETRICAL SIX-TOOTH-SHAPED MICROSTRIP ANTENNA

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Abstract. A symmetrical microstrip six-tooth-shaped antenna is considered. The influence of the main geometric parameters of the antenna on the base frequency is investigated. The main geometric parameters of the antenna include length and width of the radiator, depth of the rectangular cutouts on its radiator, thickness of the substrate, length of the ground and width of the feedline. Regression analysis is carried out and several mathematical models are constructed. The first model describes a relationship of the base frequency with depth of the rectangular cutouts, the radiator length and width. The second model describes a relationship between the wavelength at the base frequency and the geometry of the radiator. The root-mean-square error and the relative error of these models are calculated. For the base frequency and wavelength, graphs of dependencies on the geometric parameters of the antenna are plotted. We establish that a decrease in values of the base frequency and an increase in the wavelength is associated with an increase in the depth of cutouts and the radiator length. We show that a slight influence on the base frequency is caused by changes in width of the feedline, thickness of the substrate and length of the ground. The proposed formulas, describing relationships of the base frequency as well as the wavelength at this frequency with the geometric parameters of the antenna, can be used to design a six-tooth-shaped antenna in a wide frequency range.

Keywords: base frequency, wavelength, six-tooth-shaped microstrip antenna, regression analysis, antenna parameters.

1 Introduction

Microstrip antennas today are among the most widely used types of antennas in wireless communication systems [1]. These antennas have become popular, first of all, due to their small size and weight. As a result, a large number of publications on various modifications of the antennas have appeared in the literature.

The most researched antennas are microstrip patch antennas with radiators of a simple geometry. For example, a patch antenna with a rectangular radiator represents a well-studied object [1, 2]. One of the approaches to improving the antenna's properties is related to adding cutouts on the sides of the radiator or adding various slots on the radiator itself. By doing this, one can achieve a compact antenna size [3-5], tune or change the resonance frequencies [6-8], increase the bandwidth [9-11], etc.

For example, in [12], a comb-shaped microstrip antenna is considered, and the influence of various parameters of comb-shaped cutouts on the antenna operation is investigated. In [13], compactness of a design of microstrip antennas is achieved by a step-by-step approach to the formation of radiating elements. For wireless systems, the study [14] presents a simple comb-shaped microstrip antenna with seven operating ranges.

However, it is noteworthy that the process of designing any well-matched antenna is quite a long and time-consuming process. In [15, 16], the influence of the antenna geometry on its electrical characteristics is studied and mathematical models describing these relationships are constructed. Using these dependencies, one can predetermine the shape of the antenna for a given frequency range. This approach simplifies the antenna designing process and allows obtaining a well-matched antenna at a quicker time.

The structure of microstrip antennas with a symmetrical tooth-shaped radiator is derived from an antenna with a rectangular radiator by adding rectangular cutouts on the sides. This type of microstrip antennas is studied in [11, 17, 18], where the positive effect of cutouts on the main electrical characteristics of the antenna is also established.

In this paper, we consider an antenna with symmetrical six-tooth-shaped radiator. The influence of the radiator geometry on the base frequency as well as on the wavelength at this frequency is shown. Two regression models are constructed. The first model describes a relationship between the antenna base frequency and the radiator geometric parameters. The second model describes a dependence of the wavelength on the same geometric parameters of the radiator. Graphs of dependences of the base frequency as well as of the wavelength on the cutout depth are given. Below, the investigation of dependences of the base frequency on other antenna parameters is presented.

2 Problem Statement

Let us consider a microstrip antenna with a symmetrical six-tooth-shaped radiator (see Fig. 1). On the front side of the substrate of size a mm by b mm with dielectric constant ϵ_r , material density $\rho = 1000 \text{ kg/m}^3$ and dielectric loss tangent $\tan \delta$, a radiator of the size l by w with a straight feedline is placed. The width w and the length l of the feedline are 1 mm and 15 mm, respectively. On the back side of the substrate, there is a metal plate called the ground plane of length equal to a and width occupying the entire substrate. We assume that $\epsilon_r > 1$. The thickness of the substrate is 1 mm.

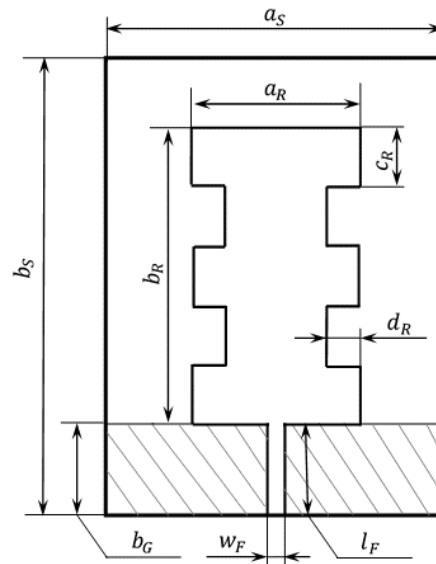


Figure 1. The structure of a symmetrical six-tooth-shaped microstrip antenna

Symmetrical rectangular cutouts of the size c_R are made on the two sides of the radiator (left and right); the width of the radiator comb d_R is calculated by the formula $d_R = a_R - 2c_R$.

Let us investigate the influence of the radiator geometric parameters on the base frequency f and on the wavelength λ corresponding to this frequency.

We perform numerical experiments in the FEKO program. In the experiments, values a_S of the radiator length are varied from 24 to 41 mm, values b_S of the radiator width are varied from 10 to 24 mm, and values c_R of the cutouts depth are changed from 0.4 to 11.9 mm (depending on the width of the radiator).

At the next step, we perform regression analysis and construct the mathematical dependences of the base frequency as well as of the wavelength at this frequency on the length a_S , width b_S of the radiator and depth of the rectangular cutouts c_R .

3 Dependence Of The Base Frequency On The Radiator Geometry

We present the dependence of the base frequency f of the microstrip antenna on the size of rectangular cutouts at the fixed radiator length $a_S = 24$ mm in Fig. 2 and at the fixed radiator width $b_S = 10$ mm in Fig. 3.

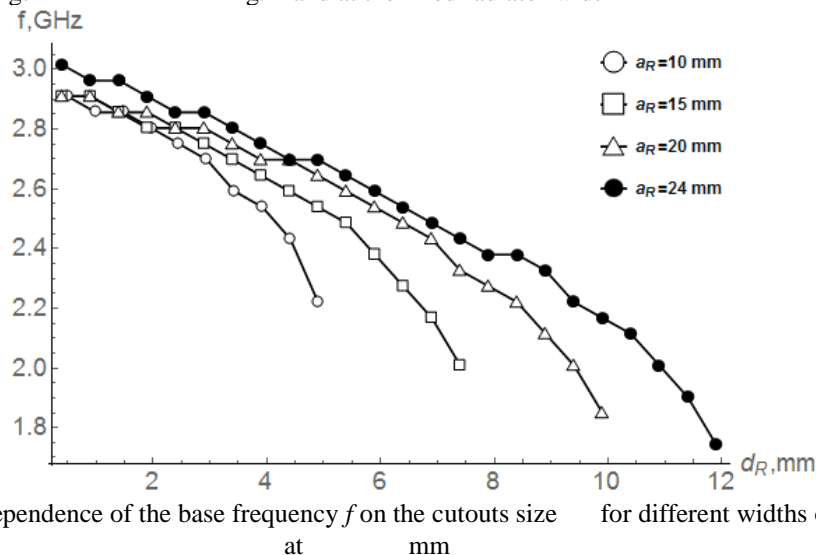


Figure 2. The dependence of the base frequency f on the cutouts size d_R for different widths of the radiator at $a_S = 24$ mm

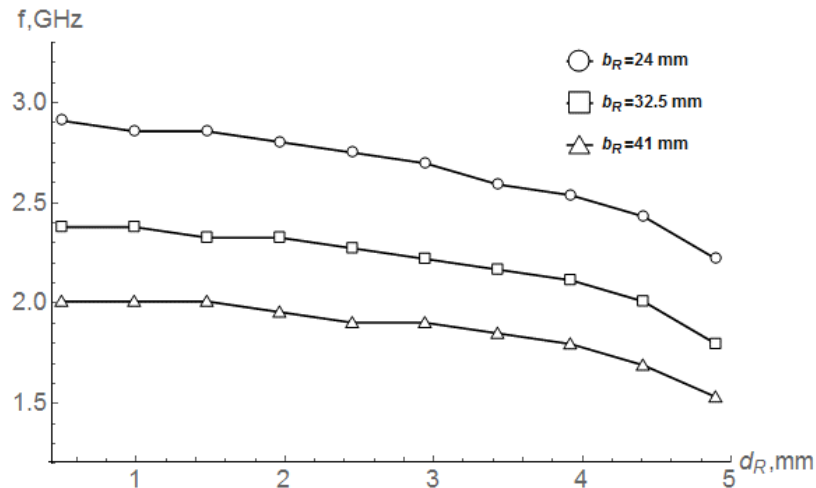


Figure 3. The dependence of the base frequency f on the cutouts size at mm for different lengths of the radiator

As shown in graphs of Fig. 2 and 3, we can see that values of the base frequency decrease with the size of the rectangular cutouts. The increasing of the radiator length also reduces the base frequency. This relationship can be explained by the fact that the current along the side walls of the radiator travels a greater distance. It follows that the radiators with the largest perimeter correspond to lower values of the base frequency.

At the next step, we consider the dependence of the wavelength at the base frequency on the size of the cutouts. We show dependences of the wavelength λ on at the fixed radiator length mm in Fig. 4 and at the fixed radiator width mm in Fig. 5

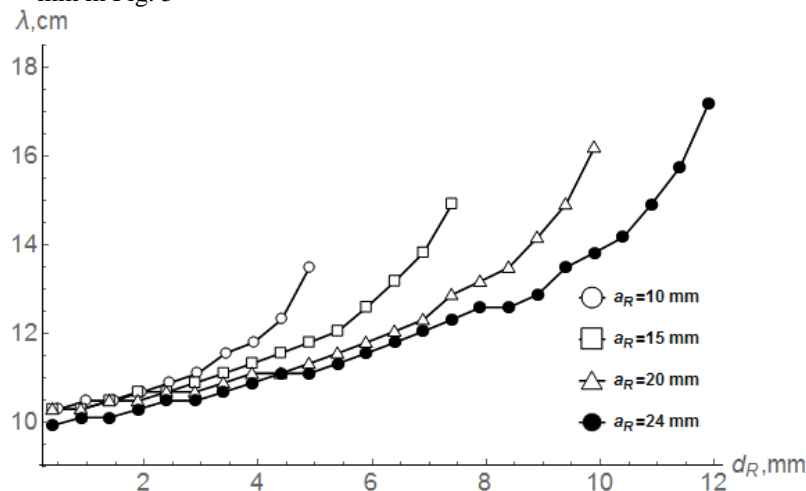


Figure 4. The dependence of the wavelength λ at the base frequency of the cutouts size of the radiator at mm for different widths

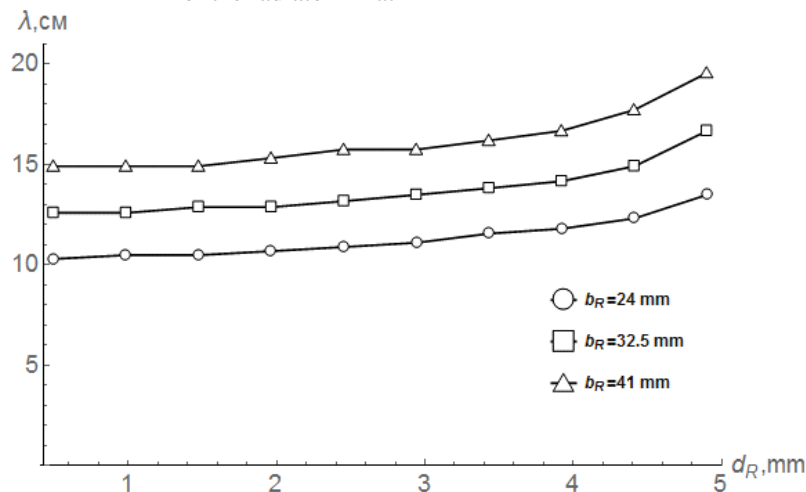


Figure 5. The dependence of the wavelength λ at the base frequency of the cutouts size for different lengths of the radiator at mm

We know that the value of the frequency is inversely proportional to the wavelength; therefore, in graphs of Fig. 4 and 5 we have an increase in values of the wavelength λ at the base frequency with an increase of cutout depth. A similar change in the wavelength occurs with an increase in length of the radiator.

Analyzing the behavior of the obtained dependences, we see that these dependences can be approximated by a certain curve. For the case of dependences of the base frequency and of the wavelength at the fixed radiator length, the corresponding curves in Fig. 2 and 4 are characterized by a high rate of change in values at the ends of the curves (rapid decrease and rapid increase, respectively). It is noteworthy that such relationships can be approximated by an exponential function. For the case of dependences of the base frequency and of the wavelength at the fixed radiator width, the corresponding curves in Fig. 3 and 5 are best approximated by a quadratic function.

In [17], we obtained that the approximate functional dependence of the base frequency on the length of a rectangular radiator has the following form:

$$f = a \cdot L^2 + b \cdot L + c, \tag{1}$$

where f is measured in GHz, and L is measured in cm.

Let us get down to the construction of a functional dependence of the base frequency on the radiator parameters L , b , and d for an antenna with a symmetrical six-tooth-shaped radiator. We seek a regression model for the base frequency in the same form as it was for a symmetrical four-tooth-shaped antenna in the study [18]:

$$f = a_1 L^2 + a_2 L + a_3 b + a_4 d + a_5, \tag{2}$$

where f is measured in GHz; the radiator length L , the radiator width b and the depth of cutouts d are measured in mm; the coefficients a_i are assumed unknown.

By using the least squares method, we determine the unknown parameters in (2); the final form of the desired functional dependence for the base frequency is following:

$$f = 0.0001 L^2 + 0.0002 L + 0.0001 b + 0.0001 d + 0.0001, \tag{3}$$

We calculate the root-mean-square error (RMSE) by using the formula:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (f_i - \hat{f}_i)^2}, \tag{4}$$

and the relative error by using the formulas of [19]:

$$\delta = \frac{RMSE}{f} \cdot 100\%, \tag{5}$$

The regression model (3) for the base frequency has $RMSE = 0.082$ GHz, $\delta = 3.05\%$. Moreover, we note that we obtained the regression model for a six-tooth-shaped antenna with almost identical high accuracy as in [18] for a four-tooth-shaped antenna ($RMSE = 0.0876$ GHz, $\delta = 3.16\%$).

Now we construct the functional dependence of the wavelength λ at the base frequency on the radiator geometric parameters. We seek a regression model in the same form as for a symmetrical four-tooth-shaped antenna in [18]:

$$\lambda = a_1 L^2 + a_2 L + a_3 b + a_4 d + a_5, \tag{6}$$

where λ , the radiator length L , the radiator width b and the depth of cutouts d are measured in mm; the coefficients a_i are assumed unknown.

Similarly, using the method of least squares, we determine the unknown parameters in (6) and the final form of the desired functional dependence for the wavelength at the base frequency is following:

$$\lambda = 0.0001 L^2 + 0.0002 L + 0.0001 b + 0.0001 d + 0.0001, \tag{7}$$

The resulting regression formula (7) for a six-tooth-shaped antenna has errors $RMSE = 3.59$ mm and $\delta = 1.63\%$. It should be noted that the model (6) for the four-tooth-shaped antenna in [18] gives errors $RMSE = 3.61$ mm and $\delta = 1.69\%$. Moreover, if one makes a judgment by using the relative error, then the functional dependence (7) for

the wavelength at the base frequency appears more accurate than (3) for the base frequency. In addition, the radiator (Fig. 1) takes a rectangular shape at $\alpha = 0$; for this scenario the following relationship

$$\lambda = \frac{C}{f} \tag{8}$$

describing a relationship of the wavelength at the base frequency with the length of the rectangular radiator holds true, where C is some constant. In our case, i.e. at $\alpha = 0$, from expression (6) we obtain a formula different from (8), but more accurate, at the same time. We can exclude the first term in the representation (6). Then the modified formula (7) has an error of about 4.5%, and this particular case coincides with the expression (8).

4 Influence Of The Main Antenna Parameters On Base Frequency

Let us investigate the influence on the base frequency of other geometric parameters of a six-tooth-shaped antenna such as the ground length b_G , the radiator dimension (RD), the substrate thickness (TS), the feedline width (see Fig. 1). We choose the radiator with dimensions 10 by 24 mm and with sizes of cutouts 0.5 and 2.5 mm for analysis.

First, we consider the influence of the ground size on the base frequency f in Fig. 6. The size of the ground will be changed by varying its height b_G .

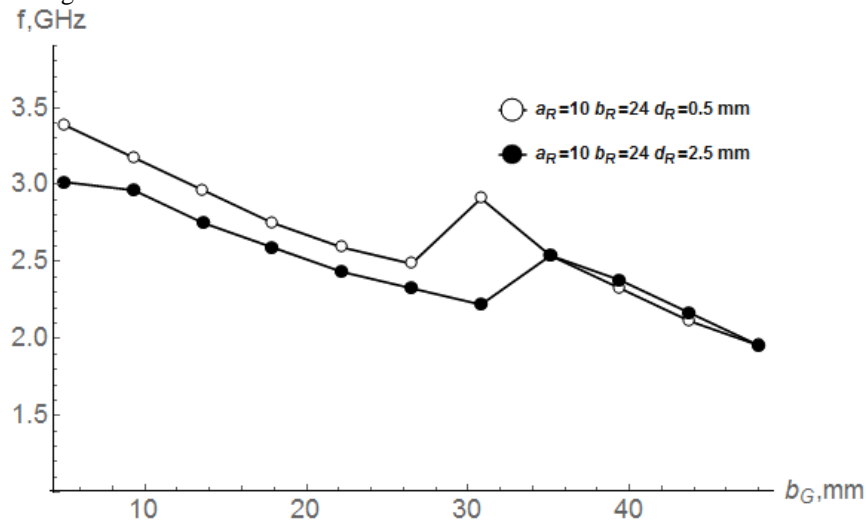


Figure 6. The dependence of the base frequency f on the ground length b_G at different depths d_R of cutouts

We note that the increase in the ground length leads to a small increase in frequency at values b_G of about 27-36 mm. This can be explained by the fact that to the ground, there also corresponds a certain resonant frequency, the value of which decreases with an increase in the ground length, since the current on the ground is to travel a greater and greater distance. At small values of b_G , the frequency of the ground has large values. However, as the ground increases, this frequency decreases and becomes the base frequency starting from a certain value of b_G . This fact can help to control two frequencies, one of which corresponds to the radiator, whereas the other one corresponds to the ground.

Let us consider in Fig. 7. the influence of the radiator dimension (RD) on the base frequency.

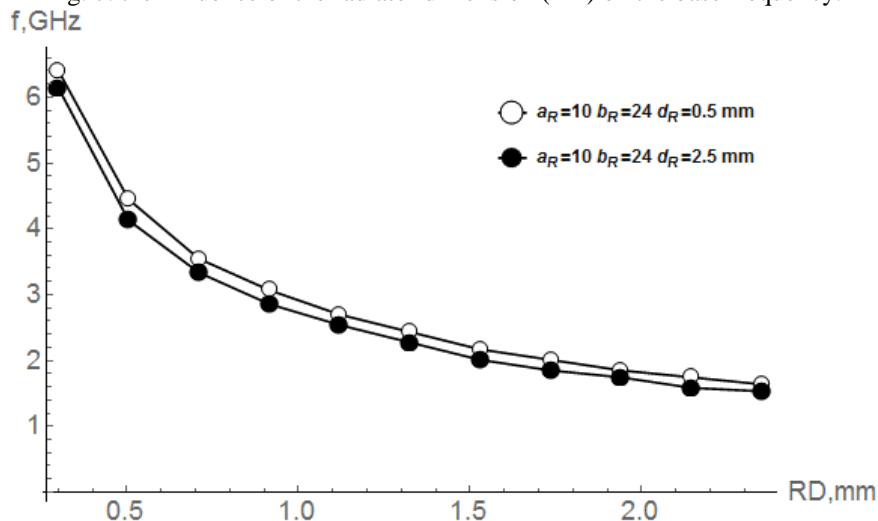


Figure 7. The dependence of the base frequency f on the radiator dimension (RD) at different depths d_R of cutouts

The graph shows that for a small dimension of the radiator $RD \leq 0.4$, we have large values of the fundamental frequency; in addition, values of f vary significantly for RD ranging from 0.1 to 1.25 mm, and then we can see a smoother decrease in the base frequency.

At the next step, we consider the influence of the thickness of the substrate (TS) on the base frequency in Fig. 8. We note that increasing the substrate thickness from 0.6 mm to 5 mm leads in a monotonically small decrease in the base frequency. Moreover, values of the base frequency, corresponding to different sizes of rectangular cutouts have a very similar behavior.

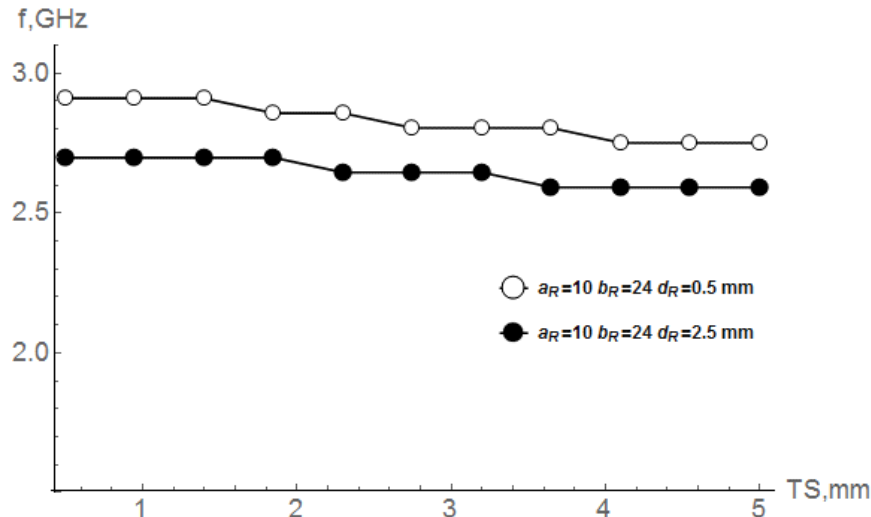


Figure 8. The dependence of the base frequency f on the substrate thickness (TS) at different depths of cutouts

We note that the substrate is homogeneous, but by choosing an inhomogeneous filling of the dielectric layer, it is possible to affect the given frequency range. Examples of the influence of the heterogeneity of filling the layer with a dielectric material on the diffraction of electromagnetic waves can be found in [20, 22].

We consider in Fig. 9 the influence of the feedline width on the base frequency.

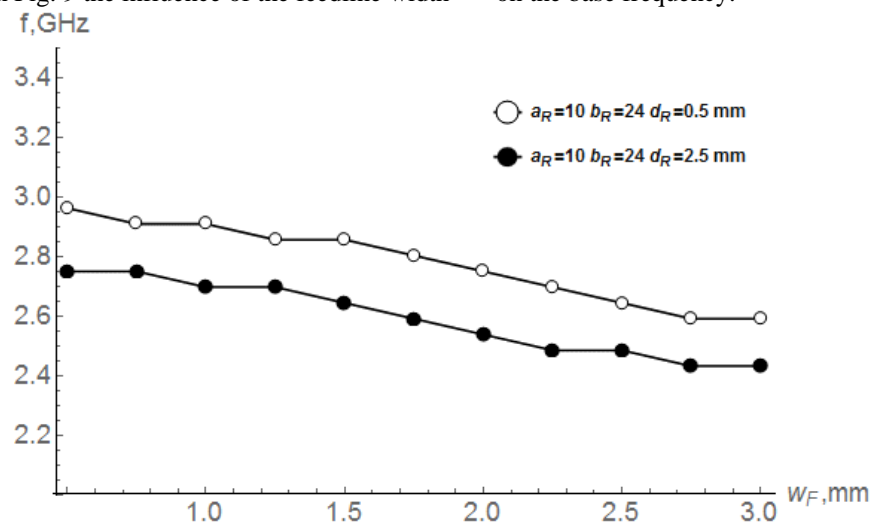


Figure 9. The dependence of the base frequency f on the feedline width at different depths of cutouts

Analysis of the graphs shows that values of the base frequency decrease monotonically with increasing the feedline width. Moreover, for antennas with different cutouts, the difference between the frequency values remains approximately the same. This suggests that changing the feedline width can slightly correct the base frequency.

5 Summary

A microstrip antenna with a symmetrical six-tooth-shaped radiator is considered.

We establish that as the depth of the rectangular cutouts is increased, values of the base frequency decrease and the wavelengths at the base frequency increase, while similar changes occur with increasing the radiator length.

We reveal that the increases in the ground length, the substrate thickness and the feedline width lead to insignificant changes in the base frequency in contrast to the increase of the radiator size.

Regression models with high accuracy are constructed for dependences of the base frequency as well as of wavelength at this frequency on the radiator width and length as well as on the depth of the rectangular cutouts. Moreover, the model for the wavelength has a smaller approximation error.

6 Conclusions

Investigated dependences of the base frequency and the wavelength at this frequency on the geometrical parameters of the radiator show a decrease in values of the base frequency and an increase in the wavelength with an increase in size of the rectangular cutouts and radiator length. For a more complete understanding of dependences of the base frequency on the ground length, feedline width, substrate thickness and antenna size, a further regression analysis can also be carried out.

We note that the regression models obtained for the base frequency and for the wavelength at this frequency provide an opportunity to simulate an antenna operating in a given frequency range.

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