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COMPUTER-AIDED DESIGN OF THE VIVALDI ANTENNA FOR ULTRA-WIDEBAND ELECTROMAGNETIC PULSE RADIATION

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Abstract. *Background*. Unmanned and remotely piloted aerial vehicles (UAVs and RPVs, respectively) have already found wide application in various areas of human life. *Materials and methods*. UAVs are actively used in agriculture, monitoring, logistics, control of hazardous objects. But, as often happens with technological progress, advanced developments are beginning to be actively used for military purposes. And today UAVs, including small ones, have become a real threat, not only to the military, but also to civilians. The purpose of this work is to substantiate the methods and means of countering strike UAVs, as well as to assess the damaging capabilities of the ammunition with the choice of the shape, mass and material of the striking elements. *Results and conclusions*. The concept of a universal ammunition capable of providing a prompt response to air threats to equipment and personnel emanating from unmanned aerial vehicles has been proposed and substantiated.

Keywords: drone, countermeasures, functional suppression, unmanned, apparatus, electromagnetic weapons

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АВТОМАТИЗИРОВАННОЕ ПРОЕКТИРОВАНИЕ АНТЕННЫ ВИВАЛЬДИ ДЛЯ СВЕРХШИРОКОПОЛОСНОГО ЭЛЕКТРОМАГНИТНОГО ИМПУЛЬСНОГО ИЗЛУЧЕНИЯ

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Аннотация. *Актуальность и цели.* Беспилотные и дистанционно пилотируемые летательные аппараты (БПЛА и ДПЛА соответственно) уже сегодня нашли широкое применение в различных областях жизнедеятельности человека. *Материалы и методы*. БПЛА активно используются в сельском хозяйстве, мониторинге, логистике, контроле за опасными объектами. Но как часто бывает при техническом прогрессе передовые разработки начинают активно применяться в военных целях. И сегодня БПЛА, в том числе малые, стали реальной угрозой, не только для военных, но и для мирных граждан. Целью данной работы является обоснование способов и средств противодействия ударным БПЛА, а также оценка поражающей возможности боеприпаса с выбором формы, массы и материала поражающих элементов. *Результаты и выводы*. Предложена и обоснована концепция универсального боеприпаса, способного обеспечить оперативный ответ на воздушные угрозы техники и личному состава, исходящие от беспилотных летательных аппаратов.

Ключевые слова: дрон, противодействие, функциональное подавление, беспилотный, аппарат, электро-магнитное оружие.

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Introduction

A technology for functional suppression of unmanned aerial vehicles (UAV) suggests using short-wave (fractions to tens of nanoseconds) electromagnetic radiation (EMR). There are two possible options for such EMR effect on electronic equipment, namely, in-band or out-of-band [6, 7].

Out-of-band functional suppression provides for the impact of radio electronic means (REM) on receivers at any frequencies outside their bandwidth, and does not require initial data on operating frequency range.

In-band functional suppression techniques provide for EMR energy losses when passing through the input circuitry of REM receiver, and depending on the ratio between the bandwidth of the reception path, and the EMR spectrum width. In-band methods are energetically most favorable, but they require initial data on technical characteristics of microwave radiation effect on UAV, and attacked or suppressed REM (e.g., the operating frequency and bandwidth of receiving devices; the clock frequency of special calculators and computers; the resonant frequency of fastener designs of radio circuit board components, etc.).

There are three fundamentally different areas for the implementation of functional suppression means using powerful short-wave EMR, and the third one being mostly widespread [1]:

1. Spark-gap and semiconductor video pulse generators.
2. Relativistic microwave radio pulse oscillators.
3. Transmitting multi-position radiation systems (MRS) and phased arrays with controlled EMR microwave focusing.

Here are the effects of ultra-short microwave radio pulses:

1. Interference: the radiation source creates electromagnetic field intensity in the operating frequency range of the target receiver. This intensity is the same or greater than the useful signal, since the receiver is unable to extract the useful signal.
2. False information: an induced electromagnetic signal sends false information into the receiver.
3. Transient destabilization: the induced voltage affects the logic state of an electronic component.
4. Permanent damage: semiconductor junctions are exposed to overvoltage, leading to their failure. However, this is due to the presence of an effective antenna system capable of transmitting power of ultra-short microwave pulses without losses [2].

Since the problem of ultra-wide range microwave radiation is associated with designing the device, it is advisable to consider an antenna operating in a wide frequency band. To create an antenna-feeder device, it is proposed to view a tapered slot antenna (TSA), which meets the requirements for creating a device for functional suppression of UAV systems by emitting an ultra-wideband and ultra-short electromagnetic pulse.

TSA, also called Vivaldi antennas (radiators based on symmetrical slot lines), posess important technical characteristics: 1) small overall dimensions; 2) small radiator weight; 3) the required radiation pattern over the entire range of operating frequencies; 4) the ability to emit ultra-short pulses.

Along with stated requirements, it is necessary to note a simple design of this type of radiators, and the ability to work in a wide range of frequencies. Based on these, it is advisable to calculate and consider such radiator for further modeling, and testing.

When calculating, the operating bandwidth mostly depends on the selected frequency, generally degrading the output matching, and on the change in the maximum of radiation pattern, beam expansion, and other parameters.

The operating bandwidth of wideband antennas should be 10 to 50% of the nominal frequency. A Vivaldi antenna is a broadband antenna, considered as a radiator of ultra-short pulses in a number of works. It should be noted that we have selected the operating frequency of 8 GHz for further calculations, as the frequency range from 5 to 8 GHz negatively affects electronic radio-elements [3].

Initially, it is appropriate to consider such radiator as an irregular transmission line harmonizing a regular line with free space. It is necessary to minimize the reflection coefficient at the input of the matching device, wherein the wave impedance and the transition length change. Thus, proper frequency characteristics (*T*-waves and quasi *T*-waves propagating in slot lines) are satisfied.

For a more accurate determination of characteristics, different calculation methods for the field along the entire slot antenna are used. A stepwise approximation by sections representing segments of a constant width slot is applied to an expansion slot according to an exponential law. This technique presents an approximate, but more accurate calculation method. For such sections, the field distribution obtained by the Galerkin method in the spectral domain is used. Thus, the field of the entire slot antenna can be defined as the sum of fields of each section.

According to this method, the field of a slot antenna with the obtained amplitude field distribution in the slot is determined. Based thereon, it is possible to consider the dielectric substrate (given a printed circuit board antenna), and the wave diffraction at the edges of an infinite height radiator.

These methods are cumbersome and inconvenient. For an approximate engineering calculation and electrodynamic modeling, software packages for calculating various types of antennas are quite suitable. For an approximate antenna calculation and simulation, it is advisable to use the CST Microwave Studio and HFSS Microwave Office computer-aided design (CAD) systems, since the theory of Vivaldi antennas is rather complicated in the field of electrodynamics (it is a traveling wave antenna). As a rule, antenna parameters are selected empirically. For further modeling of the Vivaldi antenna, it is appropriate to use the HFSS tool [4].

Approximate calculation and optimization in the CAD system

The calculation of the actual antenna length is carried out as follows:

$$L = L_{eff} - 2\Delta L,$$

$$W_{Total} = \frac{c}{2f_0\sqrt{\frac{(\varepsilon_r + 1)}{2}}},$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\left(\frac{h}{W}\right)}}\right],$$

$$L_{Total} = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0{,}824\frac{\left(\varepsilon_{eff} + 0{,}3\right)\left(\frac{W}{h} + 0{,}264\right)}{\left(\varepsilon_{eff} - 0{,}258\right)\left(\frac{W}{h} + 0{,}8\right)}.$$

The aperture geometry is calculated according to the formulas:

$$W_{\max} = \frac{c}{2f_{\min}\sqrt{\varepsilon_r}},$$

$$W_{\min} = \frac{c}{2f_{\max}\sqrt{\varepsilon_r}}.$$

where c is the speed of an electromagnetic wave propagating in a vacuum; $f_{\min}$ is the minimum operating frequency; $f_{\max}$ is the maximum operating frequency; ε_r is the permittivity.

The antenna slot width is determined by [5]:

$$W(x) = W_0 \exp\left[\ln\left(W_L\right)\left(\frac{x}{L}\right)^a\right] - \left(W_0 + b\right).$$

where W_0 is the antenna length; W_L is the total antenna width; b is the minimum aperture value of the taper; $\alpha = 0.7$.

A screenshot of this calculation results is given in Fig. 1.

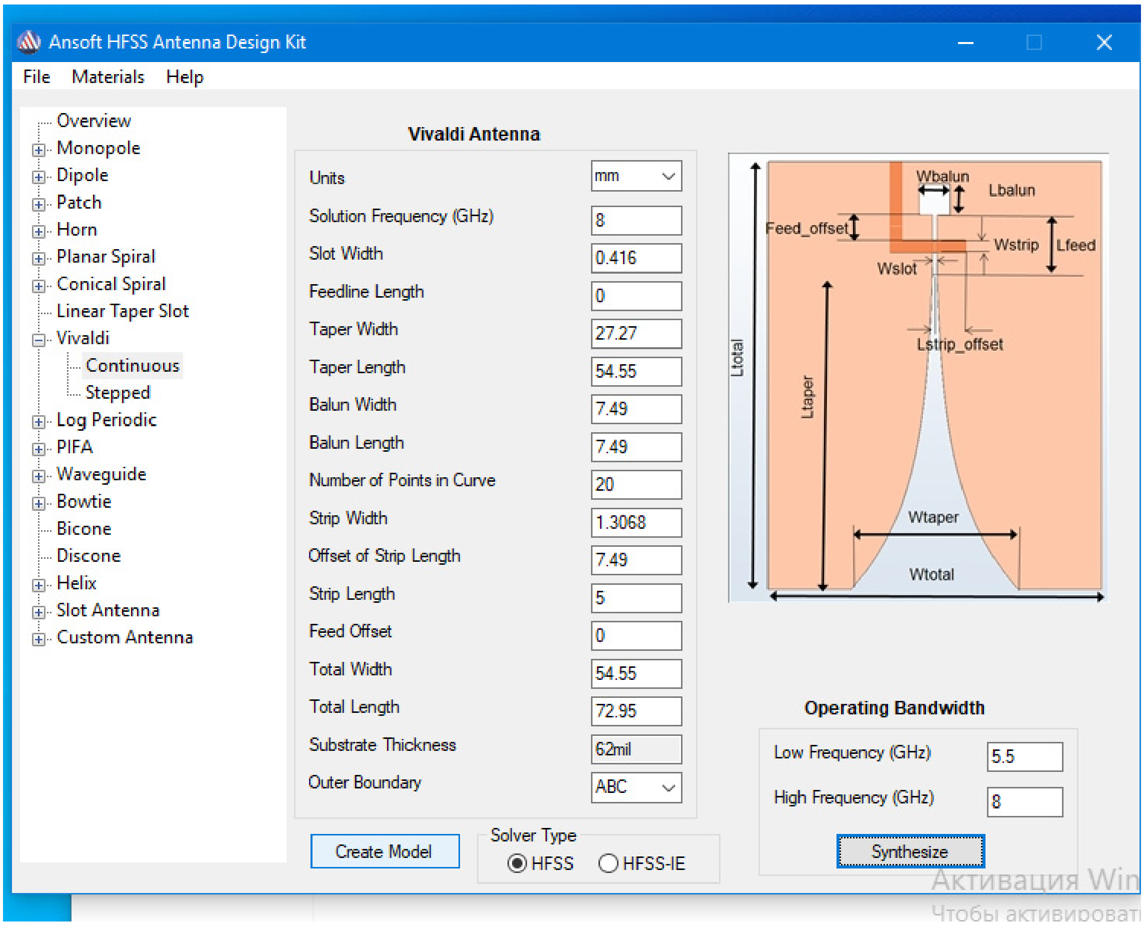

Fig. 1. Calculation program screenshot (geometric dimensioning obtained by approximate calculation)

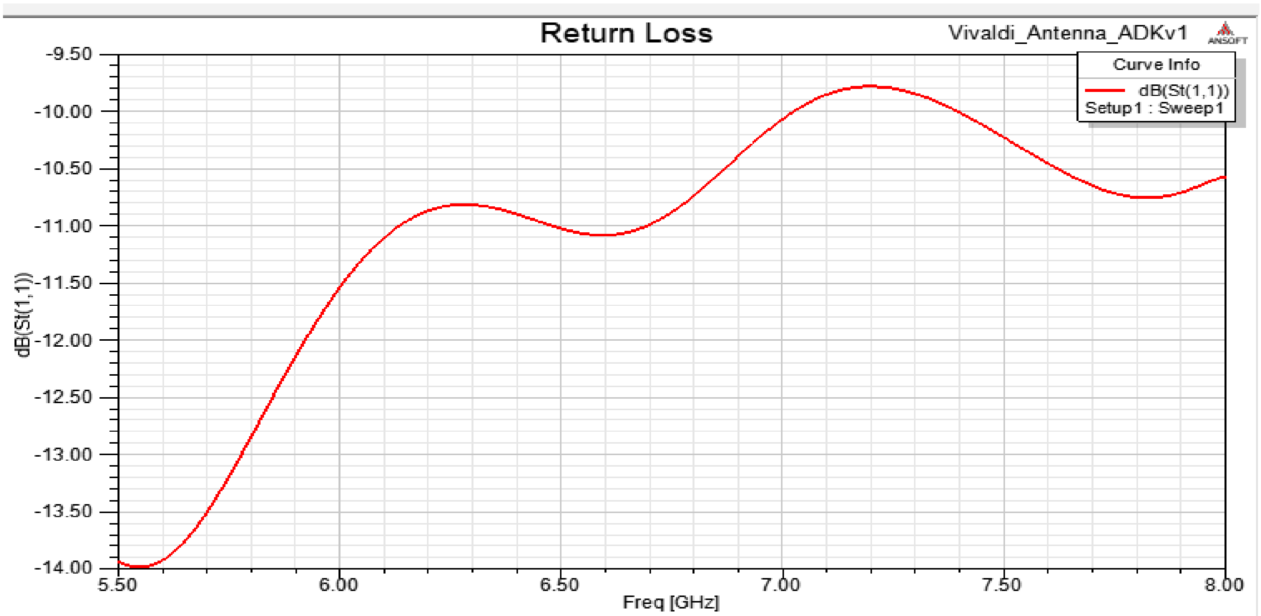

Fig. 2. Reflection coefficient versus frequency

As seen from the graph (Fig.2), the reflection coefficient is –10.5 dB at 8 GHz, being rather low. A good result is achieved from –20 dB, and it increases from 6 GHz [6].

It is necessary to perform antenna optimization (length, width, and size of the initial aperture) for its further consideration, wherein weight and size parameters should not go beyond the desired results.

First, we consider the effect of the initial aperture size W_{slot} on the reflection coefficient.

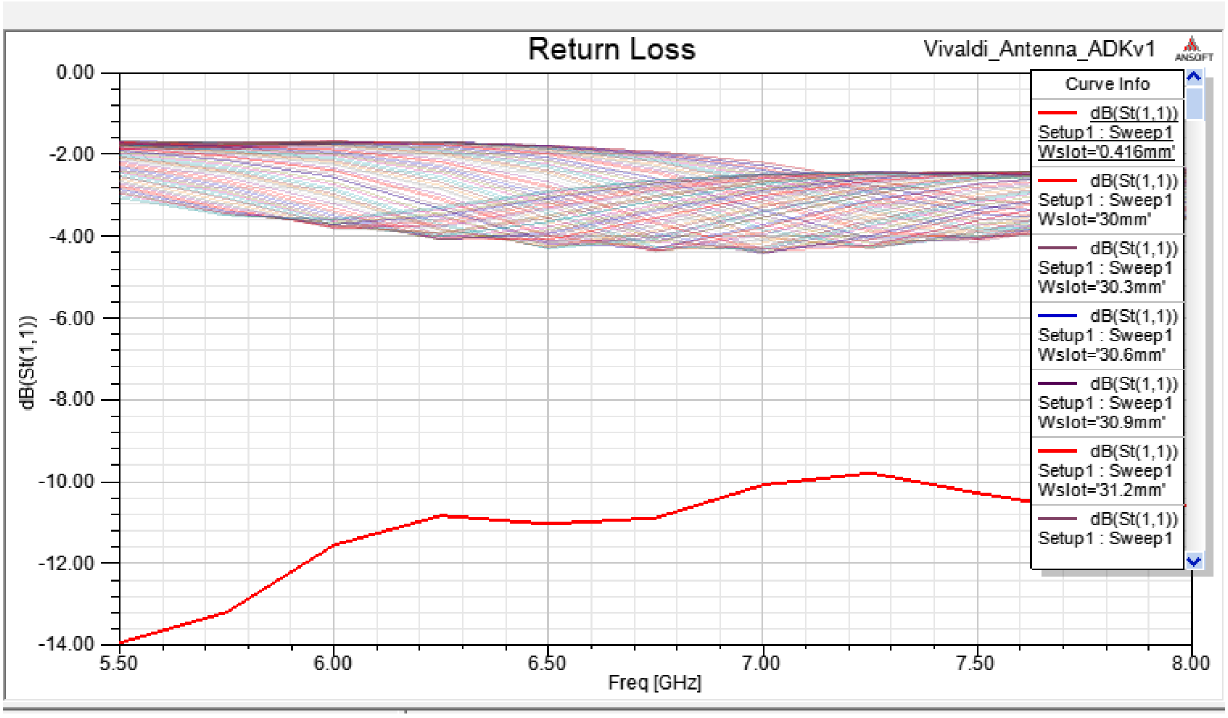

Fig. 3. Reflection coefficient optimization by varying the initial antenna aperture

As seen from the plot (Fig.3), the reflection coefficient increases with an increase in the indicator, being undesirable.

After unsuccessful optimization of the previous parameter, we have carried out optimization of the antenna length L_{total} (Fig. 4).

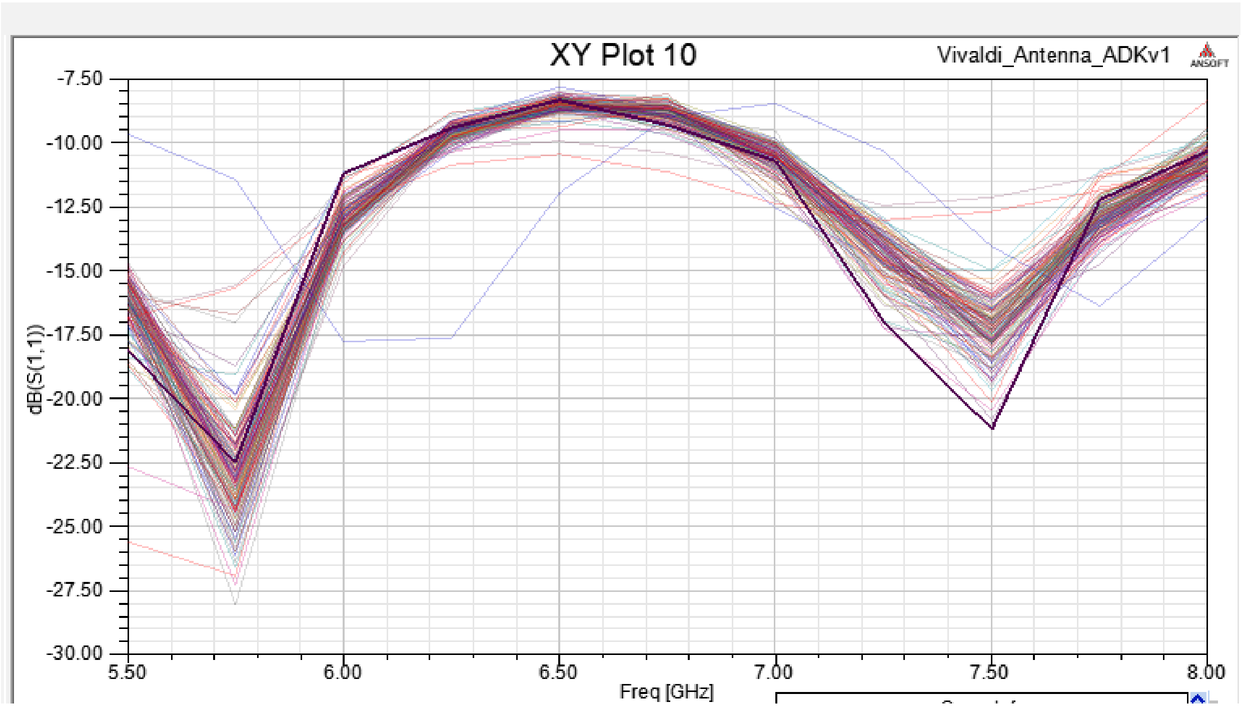

Fig. 4. Reflection coefficient optimization by varying the antenna length

In the above plot, one can distinguish a polygonal chain that meets the minimum requirements for the reflection coefficient. A genetic algorithm was chosen for the initial optimization.

It was found that the antenna length was 228.5 mm with the optimal coefficient, which satisfies the forthcoming operating conditions (Fig. 5).

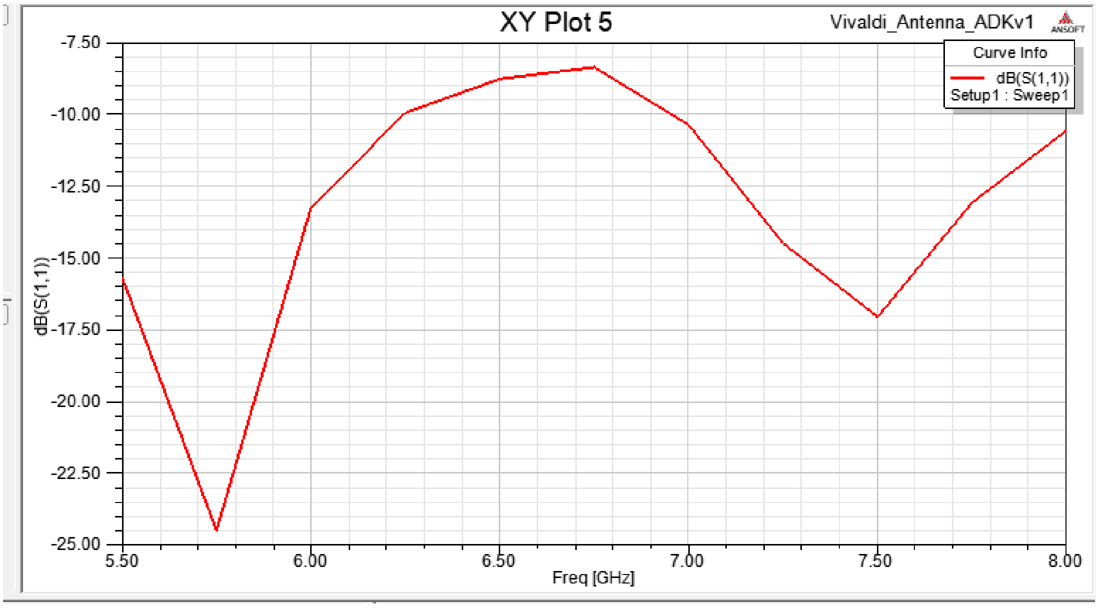

Fig. 5. Approximate optimization results in the CAD system

Thus, it was possible to reduce the reflection coefficient at a frequency of 5.7 GHz. Since the antenna is supposed to be of ultra-wideband, therefore, it is advisable to carry out further optimization so that the reflection coefficient should become acceptable at other frequencies [7].

As can be seen from the optimization plots, the reflection coefficient decreases as the width of antenna reduces. Considering this, a polygonal chain of 39.5 mm was chosen. The graph shows a more acceptable size in the 5.6 GHz domain, wherein it does not meet the specified characteristics in the 7.5 GHz domain.

Thus, the geometric dimensioning has changed after optimization (Fig.6).

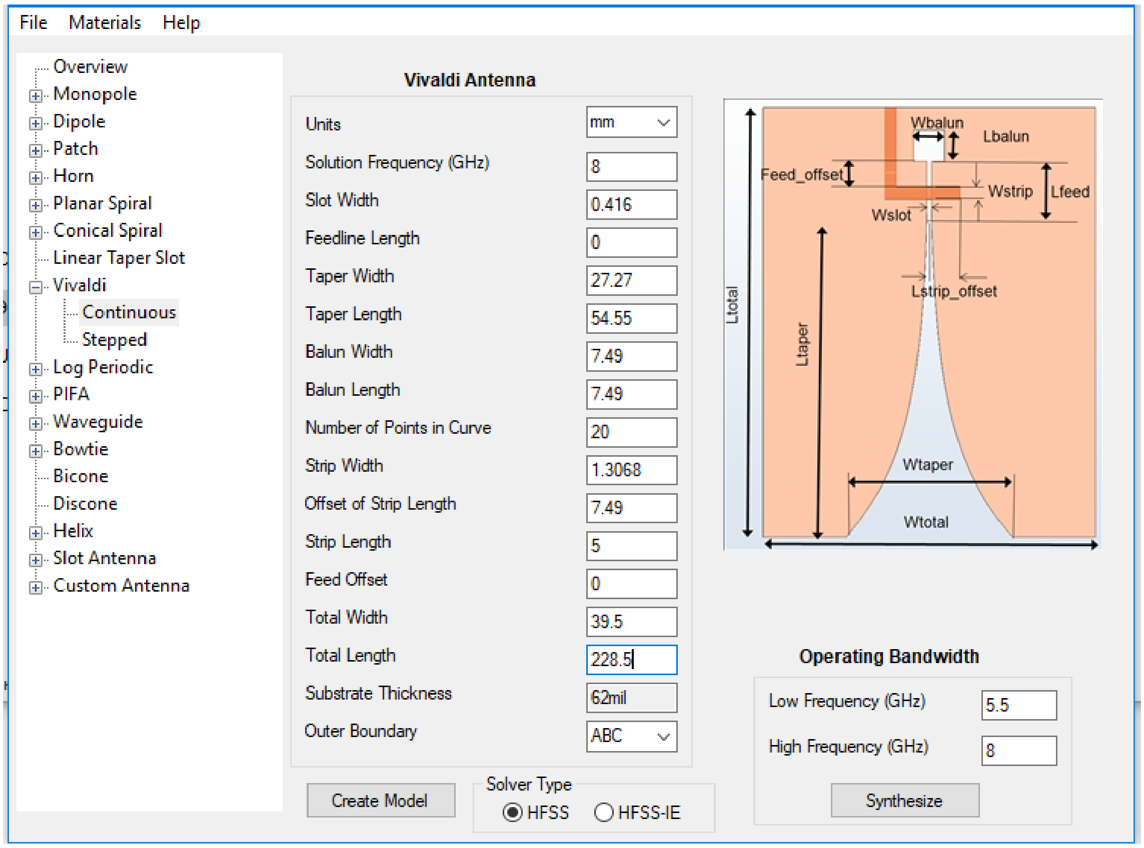

Fig. 6. The obtained antenna geometric dimensioning after optimization

Verification of the obtained results when simulating the antenna

Consider the following plot to verify the obtained antenna geometry (Fig. 7) [8].

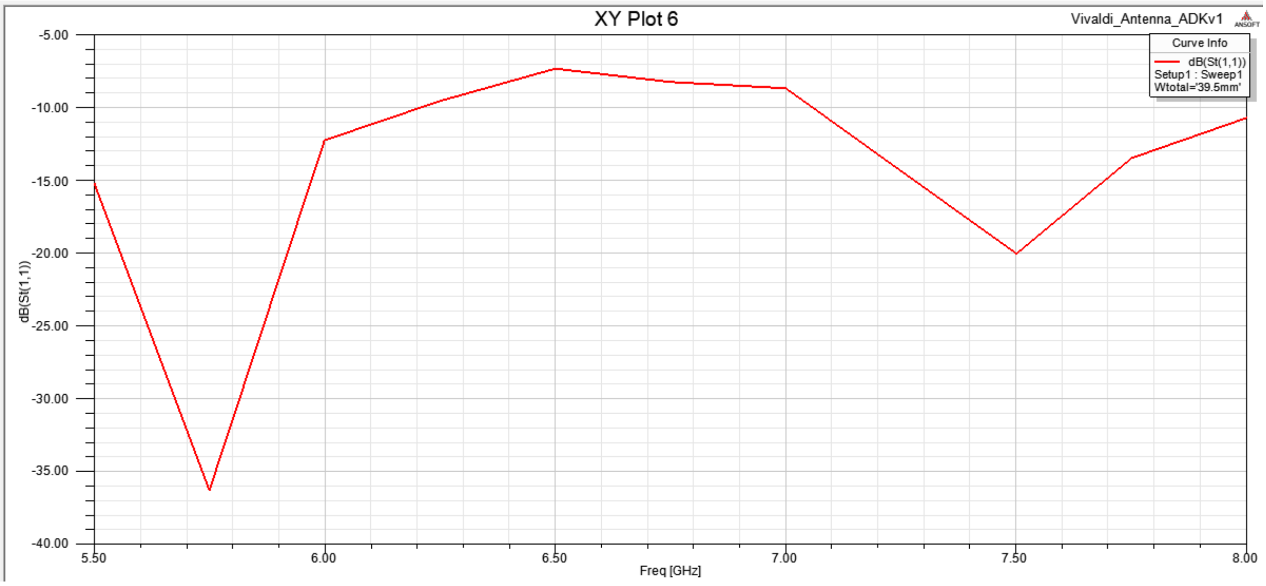

Fig. 7. Reflection coefficient of an optimized antenna simulation

A shift in $S(1,1)$ was caused by a change in active and reactive resistance. The antenna gain was modified due to an increase in the antenna geometry parameters L_{total}.

As seen from the plot (Fig. 7), the minima values are achieved at 5.6 GHz and 7.5 GHz. The indicated frequencies lie in the range of desired ones, which are negatively affect radio-electronic devices.

To construct the radiation pattern, the following formulas are used in the *H*-plane ($\varphi = 0$):

$$F_\varphi(\theta) = \frac{2\cos\theta}{\sqrt{\cos^2\theta + (\xi \operatorname{ctg} \xi k_0 d)^2}} \cdot \left(\frac{\sin(0,5k_0 \cdot a\sin\theta)}{0,5k_0 \cdot a\sin\theta}\right),$$

and in the *E*-plane ($\varphi = \pi/2$):

$$F_\varphi(\theta) = \frac{2\xi\cos\theta \cdot \cos(0,5k_0 b\sin\theta)}{\sqrt{\xi^2 + (\varepsilon\mu\cos\theta \cdot \operatorname{ctg}\xi k_0 d)^2} \cdot \left(1 - \left(k_0 \frac{b}{\pi}\sin\theta\right)^2\right)},$$

where d is the thickness; a is the width; b is the length; $k = \beta/\varepsilon\mu$; β is the propagation constant; ε is the permittivity; μ is the permeability; $\xi = \sqrt{\varepsilon\mu - \sin^2\theta}$.

The directivity is defined as follows:

$$D = \frac{4\pi U}{P_{rad}},$$

where U is the radiation intensity; P_{rad} is the radiation power.

The intense radiation power is calculated by:

$$U(\theta,\varphi) = \frac{|E|^2}{\eta_0} r^2,$$

where $|E|$ is the *E*-plane module; r is the distance from the antenna; η is the impedance of free space being 376.7 dB.

3D visualization of the radiation pattern is presented in Fig. 8 [9].

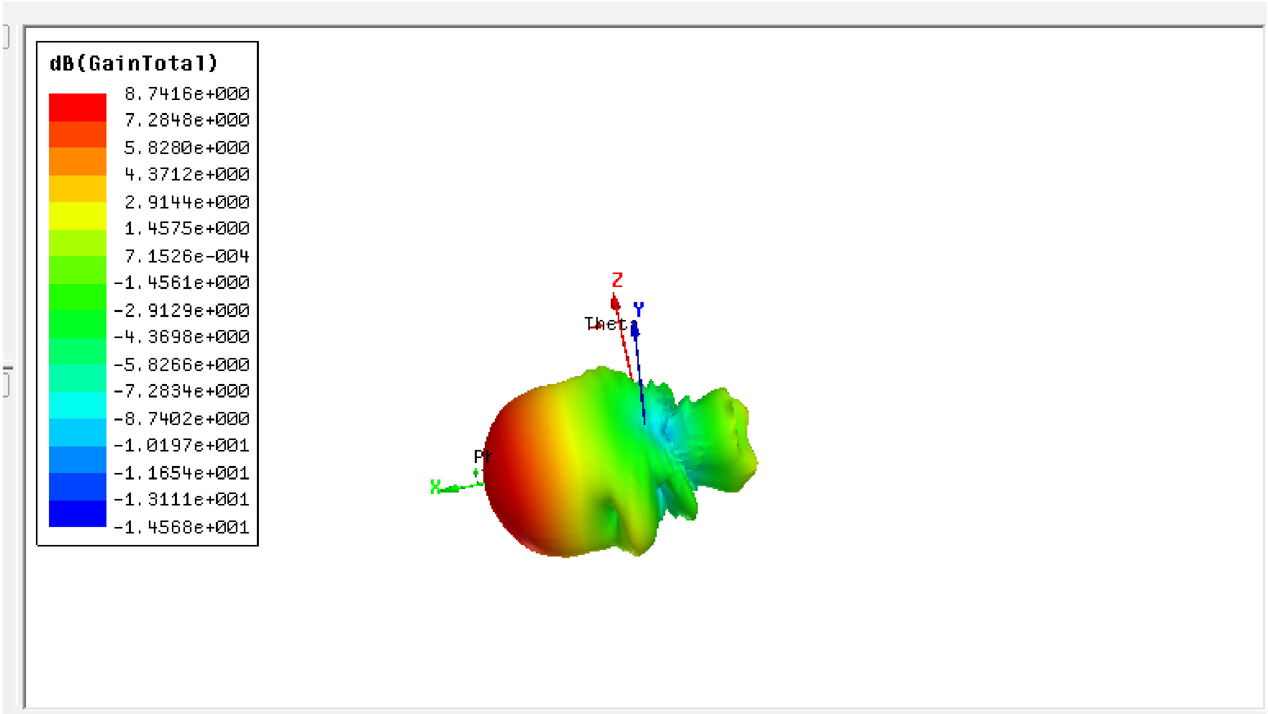

Fig. 8. Three-dimensional radiation pattern

Based on the results, the radiation pattern is wide enough, and the maximum gain is 8.7 dB for the area marked in red.

2D visualization of the radiation pattern is presented in Fig. 9.

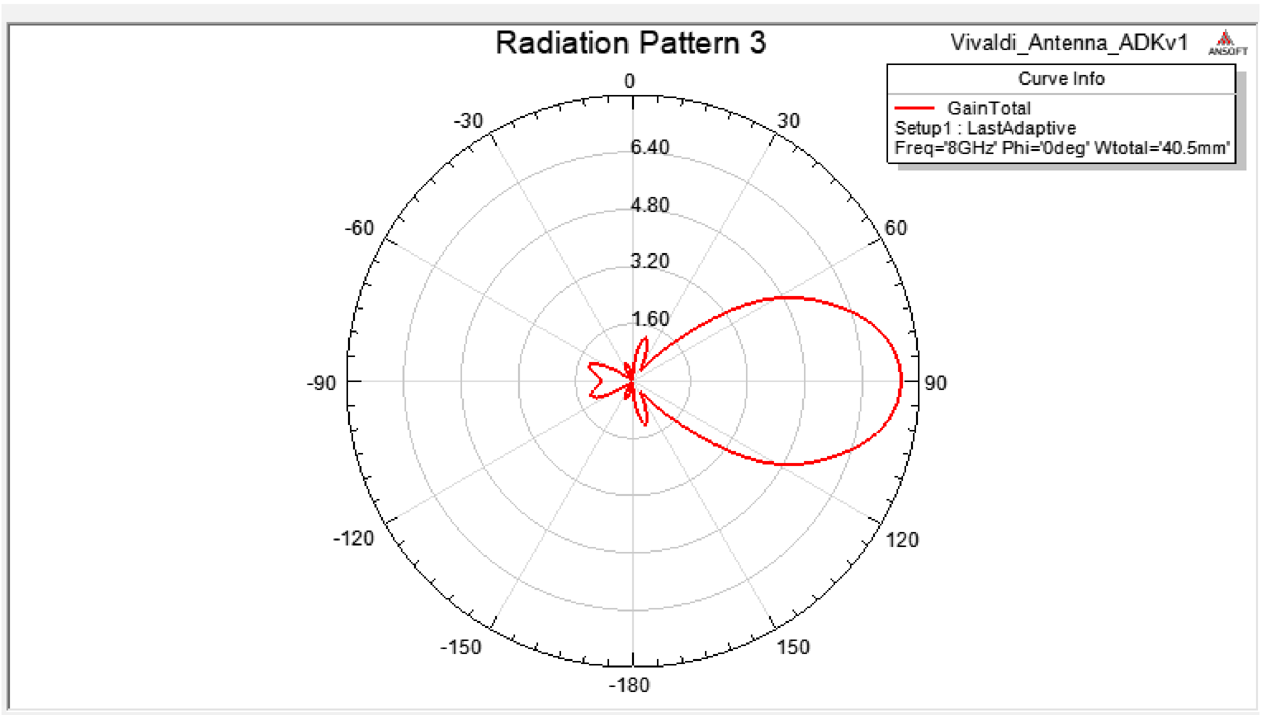

Fig. 9. Two-dimensional radiation pattern

It follows from the plot of polar coordinates that half power beamwidth (HPBW) corresponds to 60 degrees, being rather high. The side-lobe level is very low, being less than 13%.

Polarization plots in the *E*-plane and the *H*-plane are presented in Fig.10 and Fig. 11, respectively.

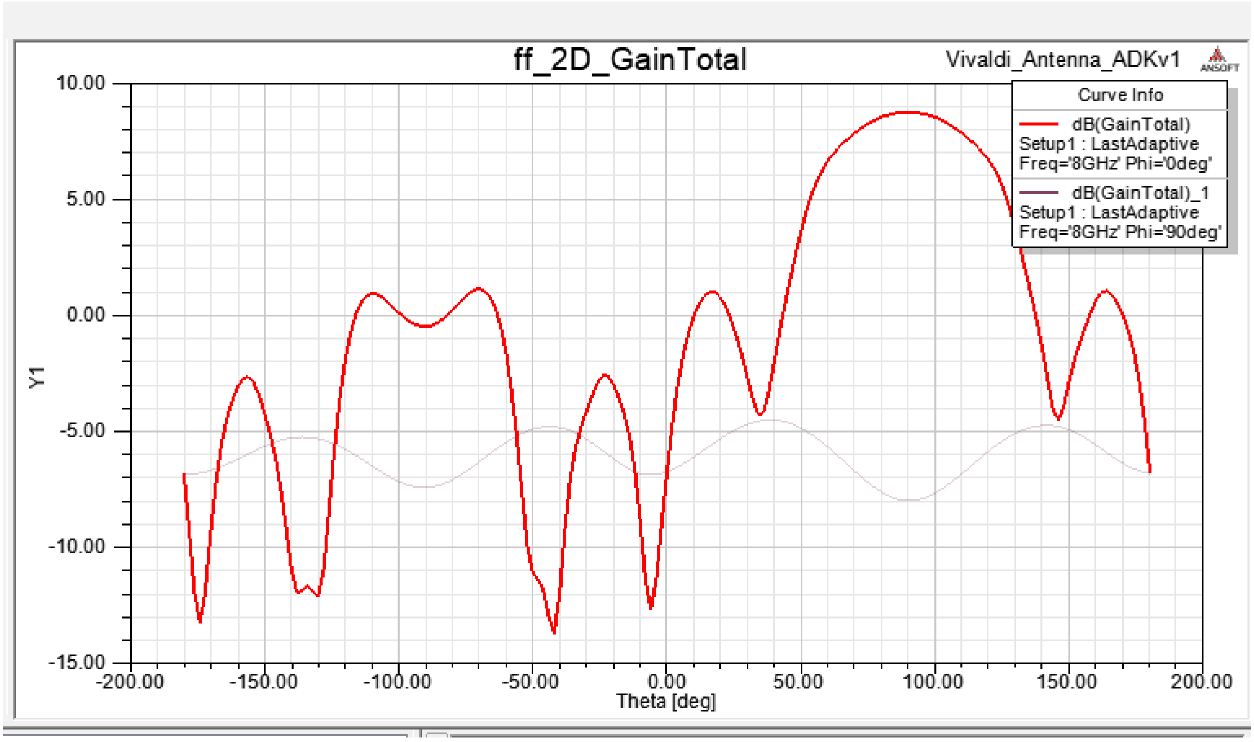

Fig. 10. Plot of polarization in the *E*-plane

The plot follows the radiation pattern in polar coordinate system, but it is presented in a rectangular shape for convenience. The main lobe gain is 8.7 dB [10].

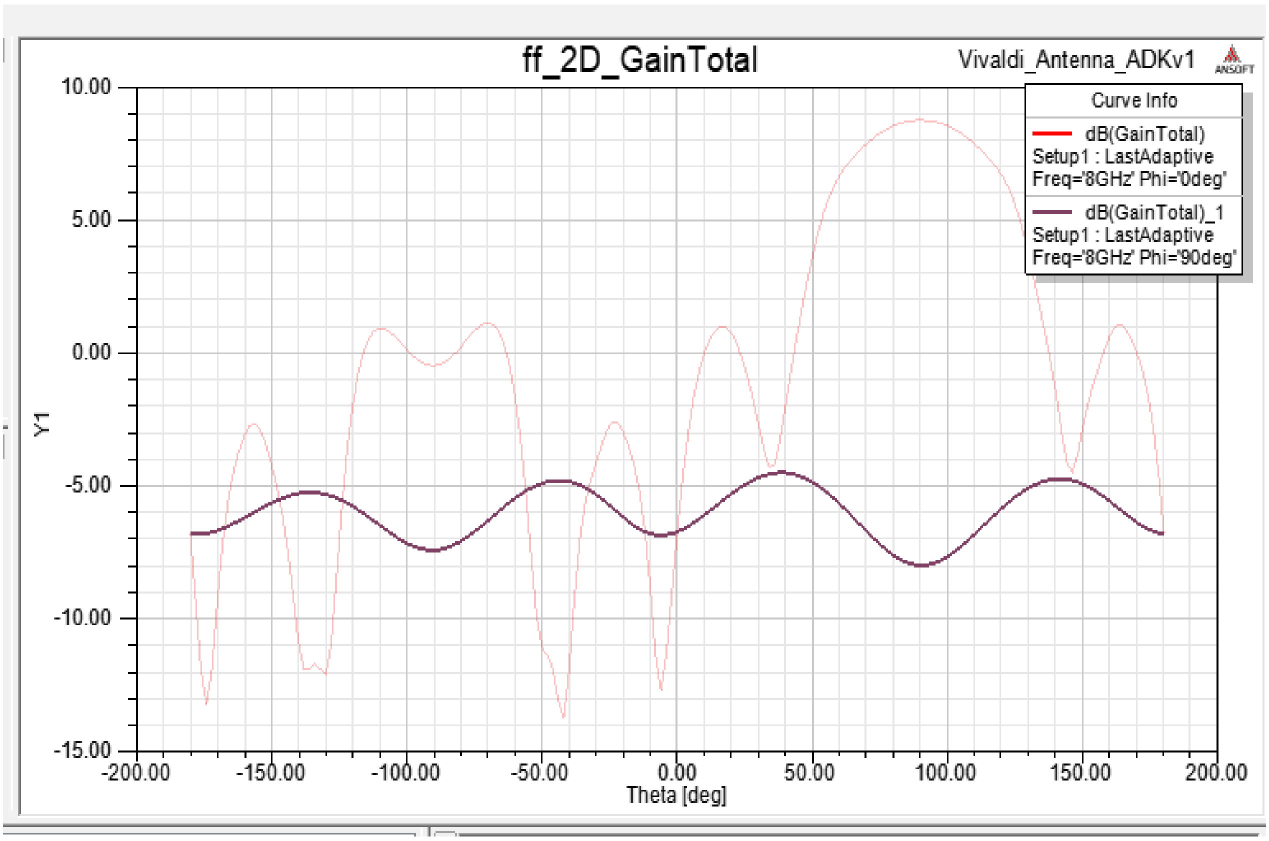

Fig. 11. Plot of polarization in the *H*-plane

The Smith chart is presented in Fig. 12.

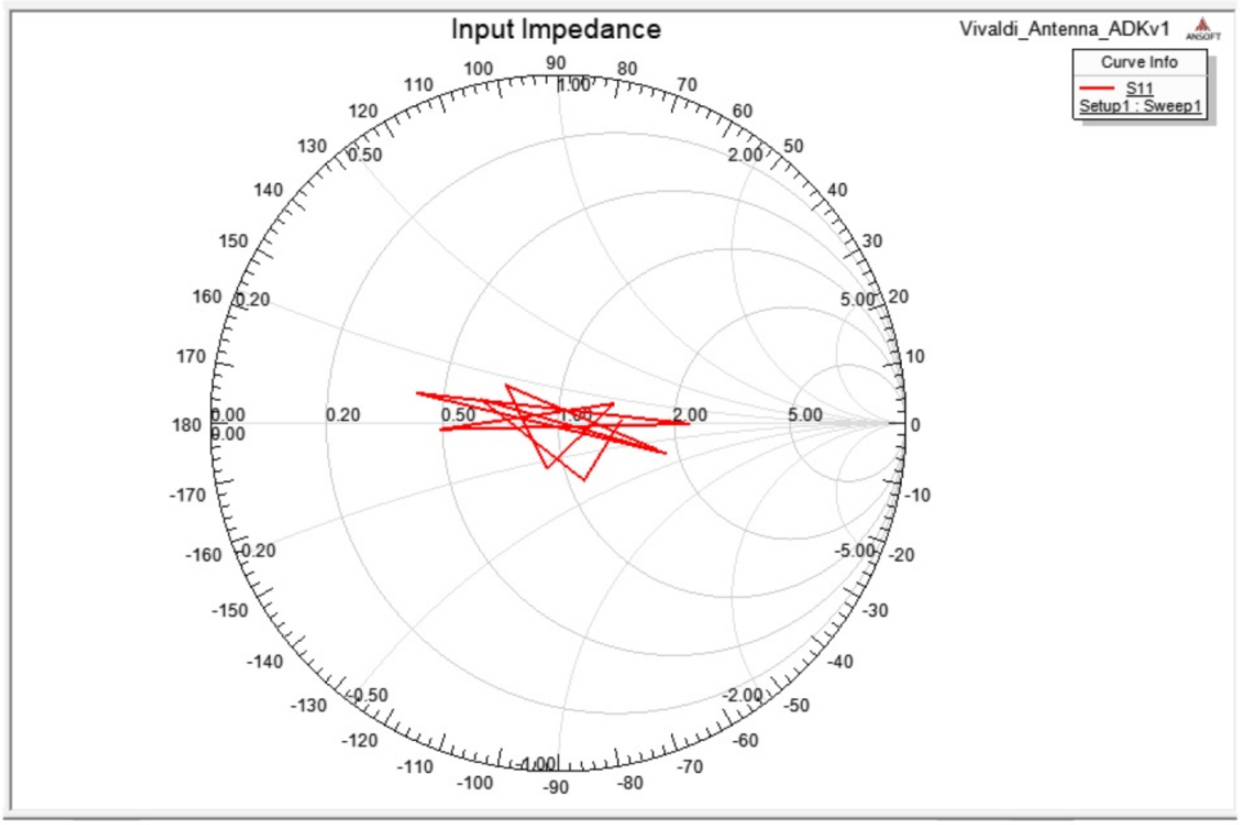

Fig. 12. The Smith chart

Simulation of antenna radiation patterns in the *E*-plane is shown in Fig. 13 and Fig. 14 [11, 12].

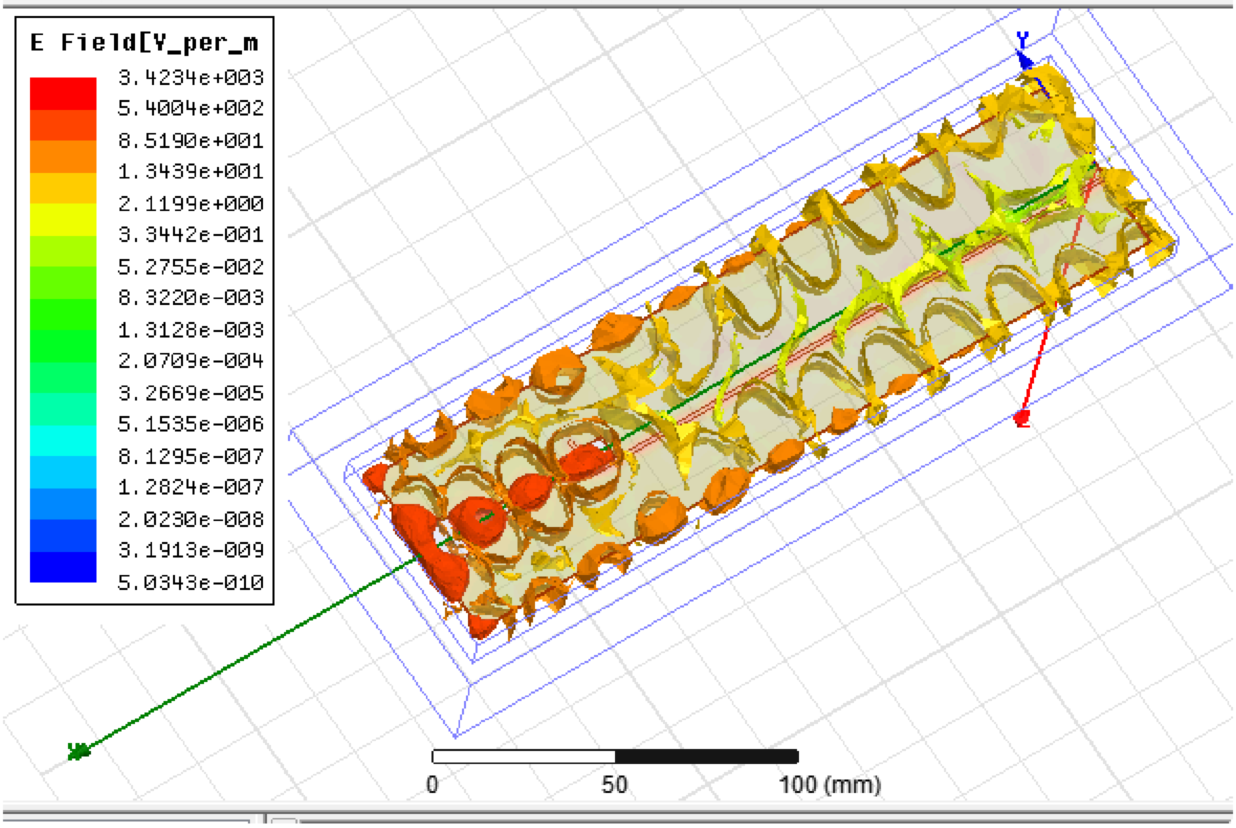

Fig. 13. Antenna radiation pattern in the *E*-plane

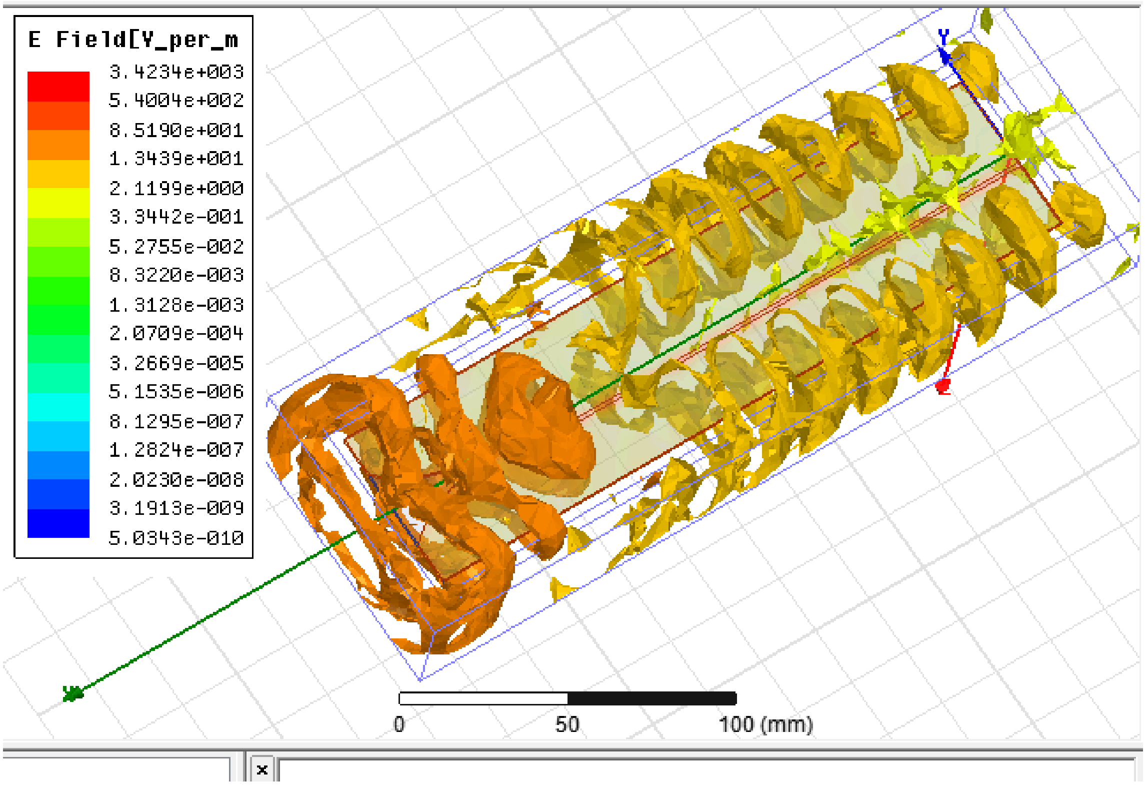

Fig. 14. Antenna radiation pattern in the *E*-plane

As shown in the above simulation screenshot in the *E*-plane, there is a strong radiation of electromagnetic field, marked in orange and yellow [13, 14].

A similar picture is observed in the *H*-plane radiation pattern shown in Fig. 15 [15, 16].

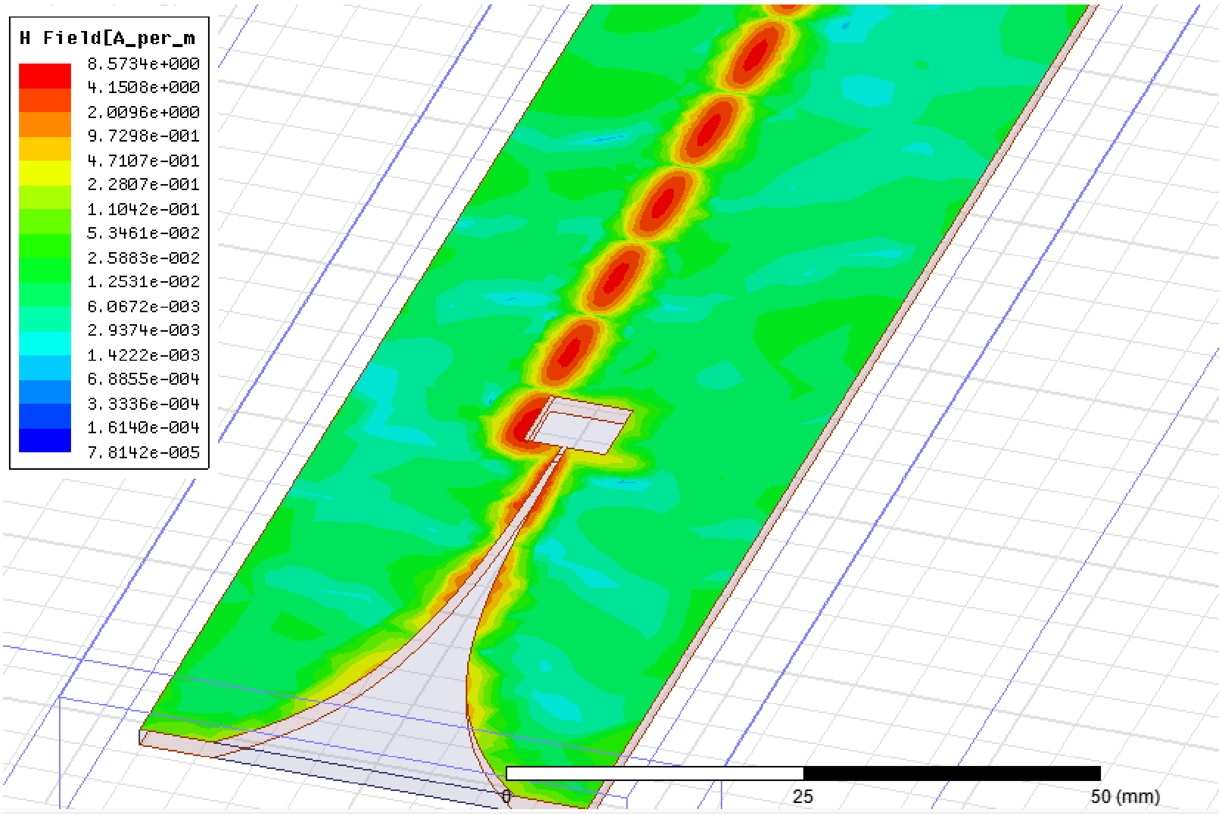

Fig. 15. Antenna radiation pattern in the *H*-plane

Conclusion

Using the finite element method, it was possible to analyze the results, calculations, and simulation of the Vivaldi antenna. Having used a genetic algorithm for optimizing the resulting Vivaldi antenna (due to changing geometric dimensioning), we have managed to achieve the acceptable characteristics of a radiator. Based on practical experience, a simplified idealized model considering mutual influence of electronic radio-elements and characteristics of filters and coils would be sufficient [17].

Based on the obtained results, one can judge the relevance of using such types of antennas in the radiation of ultra-wideband systems. Construction of a phased array based on the Vivaldi antenna, emitting in the indicated range, would be interesting from an engineering point of view [18, 19].

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