An ultra-wideband printed dipole antenna of the frequency range from 1 to 3 GHz with wide-angle scanning in the E-plane and low level of cross polarization

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Abstract. The paper presents the design of the developed ultra-wideband printed dipole antenna. The frequency characteristics of the antennas for different values of the scanning angle in the E-plane are given. When scanning in the angle sector ±50° the operating frequency band of the antenna is in the frequency range from 1 to 3 GHz at the level of the VSWR less than 3. The realized gain is up to 1.5 dB and the antenna efficiency is more than 77%. The cross polarization of the realized gain at all values of the scanning angle is less than minus 27.5 dB.

1. Introduction
When developing phased array antennas, different types of antennas are use as the radiators: open ends of waveguides [1], horn antennas [2], dipole antennas [3–5], strip antennas [6], antennas with an expanding slot – Vivaldi antennas [7, 8], etc. The choice of a particular type of antenna depends on many factors. These include the working bandwidth of the antenna and the possibility to realized wide-angle scanning. At the same time, the radiation characteristics (VSWR, realized gain, radiated power, antenna efficiency, etc.) of the antenna must meet the required values in the all operating frequency band and at all specified scanning angles.

In the case where the phased array must be ultra-wideband, the list of types of the antennas for the radiator significantly reduced. One of the most common is a radiator based on an antenna with an expanding slot, both in printed and all-metal versions – Vivaldi antennas. The operating frequency band of such a radiator can have an overlap coefficient of up to 10:1 or more. With an increase in the scanning angle sector, the overlap coefficient of this radiator decreases, but even still takes on a large value.

Despite the significant advantage over other types of antennas, the radiator based on the Vivaldi antennas has a significant disadvantage – its minimum operating frequency are related to the length of the slot, that is, the height of the antenna. As a rule, it is at least half of the operating wavelength λ, and at the maximum operating frequency, it can reach several λ at all. This fact imposes a reduction on the use of the Vivaldi antenna in the decimeter and, especially, in the meter range of wavelengths, where the height of the antenna can be tens of centimeters or more. In this regard, it is necessary to switch to the use of other types of ultra-wideband radiators.

An alternative to Vivaldi antennas is to switch to radiators based on printed dipole antennas. Such antennas are concede to Vivaldi antennas in broadband, but research shows that their height can be less than λ/2 even at the maximum operating frequency. I must say that the height of the order λ/2 at the maximum operating frequency also found in Vivaldi antennas of the «Bunny ears» type, but the price for this is a decrease in broadband. At the same time, printed dipole antennas can achieve a
height of the order $\lambda/4$ at the maximum operating frequency while maintaining a large overlap coefficient (3:1 or more). In the case of a Vivaldi antenna, the use of such a height will necessarily lead to a significant narrowing of the operating frequency band or even to the loss of the ability to antenna matching with the power line.

Previous studies have shown [4, 5] that printed dipole antennas can have a small VSWR value in an ultra-wide frequency band and in a wide sector of scanning angles. Thus, at the level of the VSWR $\leq 3$, the developed antenna has an overlap coefficient of the operating frequency range ($f_{\text{max}}:f_{\text{min}}$ ratio) of approximately 3:1 (2.3–7.0 GHz). This VSWR value is achieved in a wide sector of scan angles ($\theta = \pm 60^\circ$). However, the previously developed antenna has a disadvantage: its dimensions were so small (width (in the E-plane) was equal to $\approx 0.2 \lambda$; depth (in the H-plane) $\approx 0.15 \lambda$ and height $\approx 0.3 \lambda$) that the maximum value of the realized gain did not exceed minus 6 dB. That is, additional research was required to increase the realized gain (by increasing its electrical dimensions) while maintaining the acceptable values of other characteristics.

In connection with the above, the aim of this work was to increase the electrical dimensions of the previously developed ultra-wideband printed dipole antenna while maintaining a wide-angle scan in the E-plane ($\theta \geq \pm 45^\circ$).

2. The design of the antenna

Figure 1 shows the design of the 3D antenna model that was developed in HFSS [9]. The antenna is made of the Rogers RO4003 dielectric substrate ($\varepsilon=3.55$, $\mu=1$, $\tan\delta=0.0027$). The thickness of substrate is 0.5 mm and has double-sided metallization. This antenna powered by a 50-Ohm coaxial cable.

![Figure 1. The design of the antenna: a) general view and b) top view](image)

Previously, was this design proposed in [10] and showed good results in matching in a wide sector of scanning angles. In this regard, was additional optimization of the antenna parameters carried out in order to achieve the parameters stated in the purpose of the work, followed by the study of the remaining radiation characteristics. The overall dimensions of the antenna have the following value (depth $\times$ height $\times$ width): $30 \times 40 \times 36$ mm. the electrical dimensions of the antenna at the maximum operating frequency of 3 GHz, respectively, are equal to $0.3 \lambda \times 0.4 \lambda \times 0.36 \lambda$.

3. The characteristics of the antenna

The studies were conducted using the HFSS software [9] as part of an infinite antenna array using periodic boundary conditions. The studies were conducted in the frequency range from 1 to 3 GHz and
in the sector of scanning angles $\theta_0=\pm 60^\circ$. Since the characteristics were similar for positive and negative values of the scan angles, they will be shown only for positive values.

Figures 2–5 below show frequency characteristics of the radiation characteristics of the antenna at the different scanning angles: VSWR, realized gain, radiated power and the cross polarization of the realized gain.

Figure 2 shows that the antenna has the VSWR≤3 in the frequency range from 1 to 3 GHz when scanning in the angle sector $\theta_0=\pm 50^\circ$ and generally does not exceed 2.5. When $\theta_0=\pm 60^\circ$ in the frequency range from 1.00 to 1.08 GHz, the VSWR reaches 3.7. The VSWR≤3 while in the rest of the studied frequency range, and in the frequency range from 1.2 to 3.0 GHz VSWR≤2.5.

It should be noted that in the frequency range from 1.0 to 2.4 GHz, the VSWR changes slightly (less than 0.2) when scanning in the angle sector $\theta_0=\pm 30^\circ$. Similar VSWR behavior is observed in the frequency range from 1.4 to 2.4 GHz when scanning in the angle sector $\theta_0=\pm 45^\circ$.

**Figure 2.** The frequency characteristics of the VSWR at the different scanning angles

Figure 3 shows that the frequency characteristics of the realized gain have a smooth character (without large oscillations) and their value decreases with increasing scanning angle. The smoothness of the character is due to the small values of VSWR and an increase in the slope observed just in the lower frequencies where the VSWR is increased. Need noted that the value of the realized gain in the absence of scanning was reaches 1.5 dB, that is, 7.5 dB more than the original antenna, which was the purpose of the work.

**Figure 3.** The frequency characteristics of the realized gain at the different scanning angles
Figure 4. The frequency characteristics of the radiated power at the different scanning angles

Figure 5. The frequency characteristics of the cross polarization of the realized gain at the different scanning angles

This also explains the behavior of the frequency characteristics of the radiated power (input power is 1 W), which is shown in Figure 4. This Figure shows that the radiated power of the antenna in the sector of angles $\theta_0=\pm50^\circ$ exceeds 0.77 W, and in the upper part of the operating range - more than 0.85 W. Only at $\theta_0=\pm60^\circ$ it decreases to 0.67 W at 1 GHz, where VSWR=3.7. From the above it follows that the antenna efficiency is more than 77%, and in the upper part of the operating range is more than 85%.

Another important characteristic of the antenna is the cross polarization of the realized gain, which is shown in Figure 5. The Figure shows that its value in the entire studied frequency range and at all values of the scanning angle is less than minus 27.5 dB. This value is observed at a frequency of 3.0 GHz at $\theta_0=0^\circ$, and at frequencies less than 2.9 GHz, its value does not exceed minus 30 dB. For all other scan angles, the value of the cross polarization of the realized gain is less than minus 29 dB.

To complete the presentation of the research results, you need to look at the behavior of the radiation pattern at the different scanning angles. Figure 6 shows the radiation pattern of the antenna at a frequency of 3 GHz with different values of the scan angle.

Figure 6 shows the value of the realized gain in the direction of the specified scan angle. The results of this assessment were previously shows in Figure 3. It is worth recalling that was the antenna studied as part of an infinite antenna array, and the radiation pattern of the antenna array of finite dimensions is of practical interest.
Below, Figures 7–9 show the radiation pattern of an antenna array consisting of 16×16 elements. The radiation pattern is shown for three frequencies: 1, 2, and 3 GHz.

The radiation pattern are obtained using the built HFSS function by calculating using the radiation pattern as part of an infinite antenna array. This method of calculating the radiation pattern is not accurate, since in an antenna array of finite dimensions, the characteristics of the antennas depend on which part of the array they are located. However, this method allows you to quickly calculate the radiation pattern and make an assessment of their shape, which is exactly what you need to do at this stage of research.

Figures 7–9 show that for large values of the scanning angle, the maximum of the radiation pattern does not coincide with the specified position. This is due to the large width of the radiation pattern and the effect of the antenna array on the propagation of the electromagnetic wave that is "pressed" against it. For example, at a frequency of 1 GHz at $\theta_0=50^\circ$, the maximum of the diagram is at $\theta=42.5^\circ$, and at $\theta_0=45^\circ$ is at $\theta=42.5^\circ$. However, with increasing frequency, the beam width of the radiation pattern becomes smaller and the direction of its maximum coincides with the specified one. So at a frequency of 2 GHz at $\theta_0=50^\circ$, the maximum of the diagram is at $\theta=48.5^\circ$, and at $\theta_0=45^\circ$ is $\theta=44^\circ$, and at a frequency of 3 GHz, the direction offset does not exceed 0.5°. For $\theta_0=50^\circ$, the position of the beam at frequencies 1, 2 and 3 GHz, respectively, is at $\theta=52$, 57.5 and 58.5°.

Figure 6. The radiation pattern of the antenna at the different scanning angles

Figure 7. The radiation pattern of the of the antenna array of 16×16 elements at frequencies 1 GHz, at the different scanning angles
As for the level of the side lobes, when scanning in the sector of angles θ₀≤±50°, its maximum value at frequencies 1, 2 and 3 GHz is minus 11.4, minus 11.7 and minus 12 dB, respectively. When scanning at θ₀=±60°, the value of the side lobe level increases by about 1 dB. When scanning in the angle sector θ₀=±30°, the value of the side lobe level does not exceed minus 12.5 dB.

4. Conclusion
In the course of the research work, the realized gain of the ultra-wideband printed dipole antenna was increase on 7.5 dB. Now its value in the absence of scanning reaches 1.5 dB. The cross polarization of the realized gain at all values of the scanning angle is less than minus 27.5 dB. In this case, the operating frequency band of the antenna at the level of the VSWR≤3 is in the range from 1 to 3 GHz and the overlap coefficient of the operating frequency range, as before, is 3:1. This antenna also provides wide-angle scanning in the angle sector θ₀=±50°. In this case, the antenna efficiency is more than 77%, and in the upper part of the operating range is more than 85%.

Thus, the aim of the work is fulfill.
It should be noted that at θ₀=±60°, the VSWR of the antenna exceeds three only in the frequency range from 1.00 to 1.08 GHz and reaches 3.7 at the frequency of 1.00 GHz. Therefore, the expansion of the sector of the scanning angles can be the subject of further research.
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