# Инфокоммуникационные технологии и системы

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## WIDEBAND DIPOLE ANTENNA

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The dipole antenna providing 13 % bandwidth relative to the middle frequency with VSWR lower than 1.15 is presented. Based on the Lorentz's lemma the electrodynamic solution of the boundary problem is found in the paper. Also the principles of developing mathematical and numerical models of the antenna are discussed. The behavior of the rear and imaginary parts of the antenna input impedance and of the standing wave ratio (VSWR) in the feeder in the frequency range, as well as particular qualities of antenna pattern is presented in the paper. The good agreement between the experimental data and the calculated data obtained using a numerical model is shown. It is noted that the antenna is characterized by compactness, mechanical durability and low resistance to airflow. The antenna can be constructed as a tube or as a microstrip implementation.The possibility to provide the antenna matching with the feeder of the predefined impedance of 50 ohms, 75 ohms or another is discussed.

*Keywords: wideband antenna, dipole antenna, broadcasting, thin-wire approach, inpedance compensation.*

**Introduction**

In a number of prominent practical applications (e.g. broadcasting) it is of importance for an antenna to be matched with the feeder in a broad range of frequencies. As a rule, a wide range of frequencies is achieved by sacrificing either the level of matching with the feeder (VSWR) or the shape of the polar pattern or the size of the antenna. But this contradicts the usual requirements for antennas in a number of applications, e.g. those working on top of special towers. In this application it is vital to keep the antenna compact to lower the weight and wind load. Minimal VSWR is extremely important for broadcasting antennas for high power signal; the insignificant feedback power won't interfere with the transmitter's work. A lower number of antennas can be put on a given tower if the antennas can work in a wide range of frequencies, as then it is possible for one antenna to service several transmitters. Therefore, it is possible to reduce the weight and wind load on the tower.

The wideband dipole antenna presented in this work is a compromise solution: while keeping the size and the polar pattern insignificantly different from those of a typical half-wave dipole antenna, it provides a low VSWR in a wide range of working frequencies.

**1. Problem Setup**

The object of this paper is an original symmetric dipole antenna, which consists of two parallel dipoles placed close to each other. They are connected in two ways: first, by a "strong" distributed electromagnetic coupling and, second, galvanically, by two short-circuiters [1].

The antenna is excited in the gap between the arms of one of the dipoles by the source, connected sequentially with the matching device. At the same time, the arms of the dipole being excited are connected to a piece of a short-circuited double-wire line, acting as a balancing device.

In this study we consider the electrodynamic characteristics of this antenna, such as input impedance, matching with the feeder, and polar pattern.

The goals of this study:

1) Developing an electrodynamic model of the antenna under consideration;

2) Theoretical research of the behavior of this antenna's input resistance, its matching with the feeder and polar pattern in the given range of frequencies;

3) Experimental study of matching of a sample antenna with a feeder.

To achieve the goals above it is necessary:

– To find a solution of the boundary electromagnetic problem of exciting the antenna with a concentrated voltage source;

– To develop a numerical model of the antenna in question;

– To produce numerical research into the characteristics of the antenna stated above;

– To run an experiment with a sample antenna.

**2. The Antenna's Configuration**

The antenna consists of (see Fig. 1) the first dipole (1 in the figure), the second dipole (2), first and second short-circuiters (3), the balancing device (4), the device compensating the reactive part of input impedance of the antenna (5), the feeder (6), the radio frequency connector (7). The first dipole consists of the first (8) and second (9) arms, set apart horizontally, creating a gap between them. The second dipole does not have a gap and is positioned in parallel with the first dipole in a distance much smaller than the wave length. The short-circuiters galvanically connect the first and the second vibrators. The antenna is excited by power delivered through a twin-axial cable (6). The balancing device used in the antenna is a short-circuited quarter-wave-length piece of a double-wire line. The twin-axial cable goes through one of the tubes of the balancing device and the corresponding arm of the first dipole. The outer conductor of the cable is connected in the gap with the first arm of the dipole. The central conductor of the twin-axial cable is connected to the central conductor of the balancing piece of the cable, which is located inside the second arm of the dipole. The second end of the central conductor of the matching piece of the cable is not connected to anything. The outer conductor of the matching piece of the cable is connected galvanically to the second arm of the dipole at the gap. As a result, the source of power is located symmetrically with respect to the antenna's structure. One pole of the source is connected directly with one of the arms of the dipole, while the other pole is connected to the other arm through the balancing device [1–4].

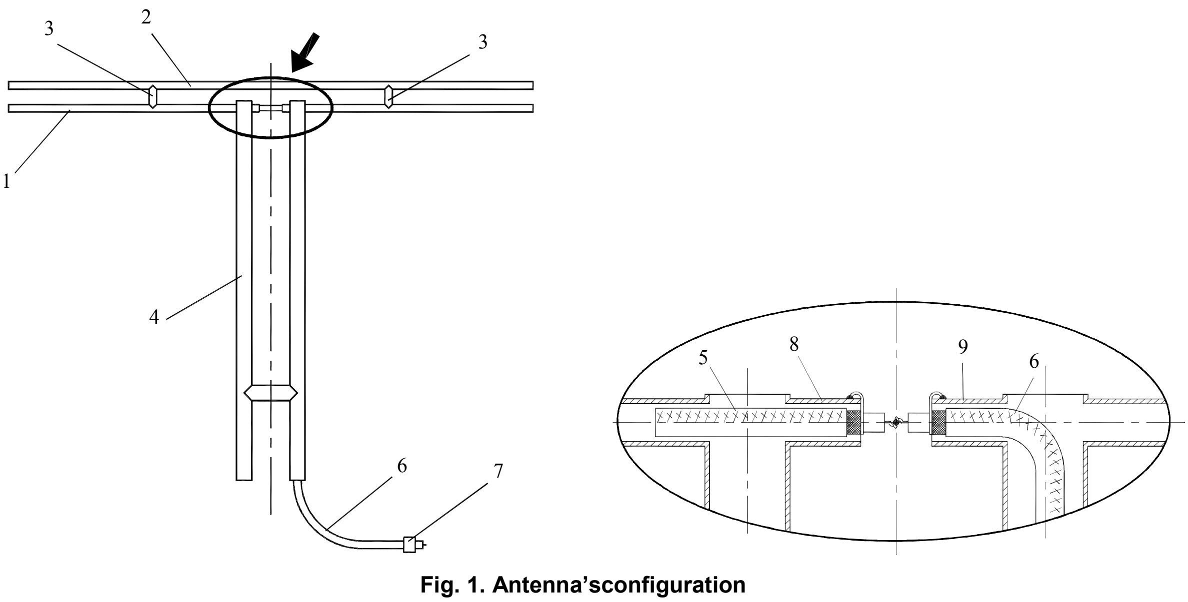



**Fig. 1. Antenna'sconfiguration**

**3. The Antenna's Principle of Operation**

As a physical model, the wideband symmetric dipole antenna under consideration is a pair of parallel half-wave dipoles with a "strong" distributed electromagnetic coupling, also having a galvanic coupling through two short (compared to the wave length) conductors (short-circuiters). The antenna is excited by a power source, connected sequentially with a matching device in the form of a piece of twin-axial line, in the gap between the arms of one of the dipoles; at the same time, the arms of the dipole being excited are connected to a piece of a short-circuited double-wire line. The length of the double-wire line is equal to a quarter of the wave length at average working frequency. The short-circuited quarter-wave piece of the double-wire line acts as a balancing device. It is assumed that the dipoles, short-circuiters and the balancing device are made of cylindrical conductors, the radii of the cylinders being much shorter than the wave length. All conductors are made of perfectly conductive material. The tangential part of the electromagnetic field density on the conductors' surface equals zero.

### 4. The Solution of the Electrodynamic Problem

Let the antenna be in a linear isotropic space with parameters μ, ε, $\sigma = 0$. While deriving the formulas, we shall use the International System of Units SI and the temporal dependency of complex values in the form $e^{-i\omega t}$.

To create the mathematical model of the antenna, let's use the reciprocal theorem in the integral form [5]:

$$\int_{\upsilon} \vec{j}_1 \vec{E}_2 d\upsilon = \int_{\upsilon} \vec{j}_2 \vec{E}_1 d\upsilon \,, \tag{1}$$

where $\vec{E}_1$, $\vec{E}_2$ are the densities of electric fields, satisfying the principle of radiation at infinity and created by independent currents with conductivity $\vec{j}_1$ and $\vec{j}_2$ respectively; $\upsilon$ is an arbitrary volume in which the sources $\vec{j}_1$, $\vec{j}_2$ are located.

Consider the antenna as a cylindrical conductor, with the diameter much smaller than its length. Suppose current $\vec{j}_1$ is excited by a power source located in the antenna's gap, and runs over the antenna's surface (Fig. 2). The distribution of current on the surface of the antenna is such that the boundary condition holds on the surface of a perfect conductor, i.e. the tangential component of the electric field density equals zero.

Consider a linear electric current source, which we will further call "a test dipole", following the work of Richmond [6–7]. Let $\vec{I}_2$ be the conduction current in the test dipole.

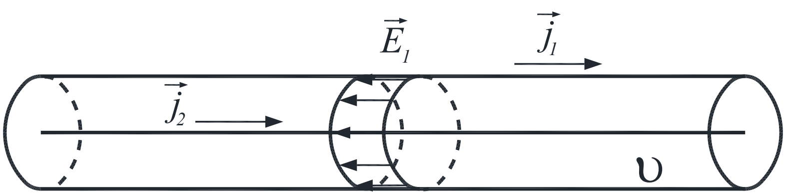



**Fig. 2. The antenna and the test dipole**

Place the test dipole on the axis of the antenna under consideration.

The integrands' values in the left and right hand sides of the equation (1) are different from zero only in the points in which the conduction current exists: more precisely, the surface current on the antenna's surface and the linear current on the interval $l_2$, occupied by the test dipole. Therefore, the integral on the left hand side of (1) with respect to volume υ can be replaced with an integral with respect to volume $\upsilon_1$, limited by a surface, coinciding with the external surface of the antenna, while the integral on the right hand side with respect to volume υ can be replaced by a linear integral, keeping in mind that $\vec{j}_2 d\upsilon_2 = I_2 d\vec{l}_2$.

Then we get:

$$\int_{\upsilon_1} \vec{j}_1 \vec{E}_2 d\upsilon_1 = \int_{l_2} I_2 \vec{E}_1 d\vec{l}_2 . \tag{2}$$

In the theory of integral equations of the wire antennas it was shown that when using a thin wire approximation, one can replace a surface electric current on a surface shaped as a round cylinder with an equivalent linear source, parallel to the axis line and located in a distance equal to the radius from the antenna's axis. Following Richmond, call this equivalent linear source "the true dipole". Then the integral with respect to volume $\upsilon_1$ can be reduced to a linear integral:

$$\int_{\upsilon_1} \vec{j}_1 \vec{E}_2 d\upsilon_1 = \int_{l_1} I_1 \vec{E}_2 d\vec{l}_1, \tag{3}$$

where $I_1$ is the net current in the section of the antenna's conductor.

Assuming that the vector of density of the electric field consists of only a component, parallel to the axis of the conductor, from (2) and (3) we get:

$$\int_{l_1} I_1 E_2 dl_1 = \int_{l_2} I_2 E_1 dl_2. \tag{4}$$

Let the distribution of current in the test dipole be

$$I_2(z) = \frac{\sin k\left(h - |z|\right)}{\sin kh}, \tag{5}$$

where $h$ is the dipole arm's length, the $z$ coordinate is taken from the dipole's center, $k = 2\pi \cdot \lambda^{-1}$ is the wave number.

Given a known current in the test dipole, using the method of retarded potentials, we can find the value of the density of the electric field $\vec{E}_2$ on the axis of the equivalent linear source.

Let the equivalent linear source be separated into $N$ segments, such that every segment is defined by three points: its starting point, midpoint and endpoint. The starting point of some $nth$ segment coincides with the midpoint of the $(n-1)$st segment, while the endpoint coincides with the midpoint of the $(n+1)$st segment. The current $I_1(z)$ in the antenna in question is approximated by piecewise-sinusoidal functions

$$I_1(z) = \sum_{n=1}^{N} I_n(z); \tag{6}$$

$$I_n(z) = \begin{cases} \dfrac{I_n \sin k(z - z_{n-1})}{\sin k(z_n - z_{n-1})}, & z \in [z_{n-1}, z_n]; \\ \dfrac{I_n \sin k(z_{n+1} - z)}{\sin k(z_{n+1} - z_n)}, & z \in (z_n, z_{n+1}]; \\ 0, \quad z \notin \left[z_n, z_{n+1}\right], \end{cases} \tag{7}$$

where $I_n$ is the current amplitude in the $n$th test (or true) dipole.

$I_n$ are the unknown quantities in (7). Essentially the antenna being considered is replaced with a collection of $N$ dipoles with sinusoidal distribution of current (see Fig. 3). $I_n$ is in fact the current amplitude in the $n$th dipole. When evaluating the integral in the left hand side of (4), normalize both summands by $I_n$:

$$\int_{l_1} I_n E_2 dl_1 = I_n \int_{l_1} \frac{I_n(z)}{I_n} E_2 dl_1. \tag{8}$$

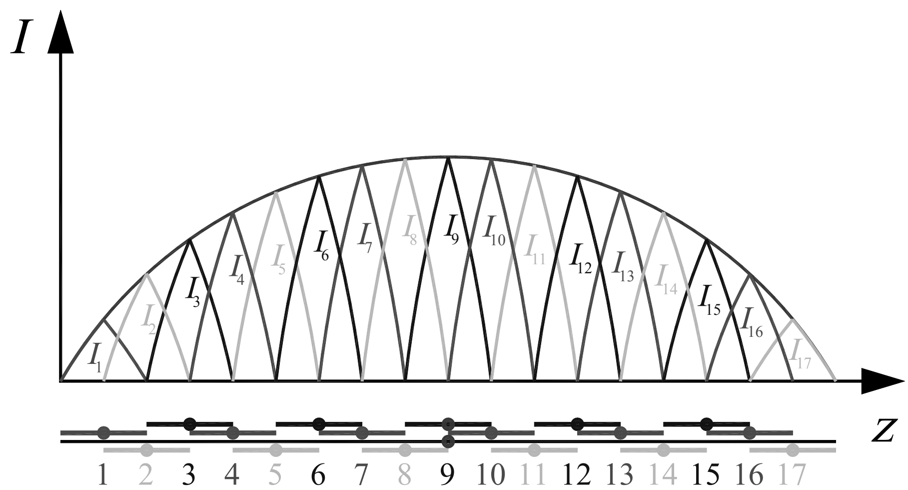



**Fig. 3. Finding the full current distribution along a linear antenna from the currents of separate dipoles**

The integral in the right hand side of (8) now defines the reciprocal reaction of two dipoles, through either of which the current is running with unit amplitude. Therefore, the integral in the right hand side of (8) represents the reciprocal impedance of two parallel infinitely thin dipoles, separated in longitudinal direction by a distance equal to the radius of the conductor of the wire antenna. (The dimensionality of this integral in Ohms results from dividing it by the square of the current amplitude, which is equal to one.)

Then the right hand side of (8) is a product of the unknown current amplitude in the $n$th dipole $I_n$ and the reciprocal impedance of the $n$th dipole and the test dipole. Then in the left hand side of (4) becomes a sum, with each of the summands being a product of the unknown current amplitude in the $n$th dipole $I_n$ and the reciprocal impedance of the $n$th dipole and the test dipole.

Now consider the integral in the right hand side of (4).

The value of the density of the electric field $E_1$ is non-zero only in the gap of the dipole, where

$$E_1 = -V_0 \cdot \Delta^{-1}, \tag{9}$$

where $V_0$ is the voltage of the source that is used to excite the dipole; $\Delta$ is the length of the gap.

Outside of the gap $E_1$ is equal to zero.

Therefore, the integral in the right hand side of (4) is equal to $-V_0$ if the $z$-coordinate of the $n$th dipole and the test dipole coincide and equal to 0 otherwise.

Then for each test dipole we can write down the following equation:

$$V_m = \sum_{n=1}^{N} Z_{mn} I_n , \tag{10}$$

where $V_m$ is the current source of the $m$th dipole, affecting the currents in every dipole through their mutual resistance $Z_{mn}$.

The mutual resistance of the $m$th true dipole and the $n$th test dipole, given the piecewise-sinusoidal distribution of current in the dipole, can be calculated with the following formula:

$$Z_{mn} = -\int_{l_{n-1}}^{l_n} \frac{\sin k(l_n - l)}{\sin kd_{n-1}} \vec{h}_{n-1}\vec{E}_m dl - \int_{l_n}^{l_{n+1}} \frac{\sin k(l - l_n)}{\sin kd_n} \vec{h}_n \vec{E}_m dl, \tag{11}$$

where $l$ is the coordinate along the axis of the segment; $d_{n-1}$ and $d_n$ are the lengths of the respective segments; $\vec{h}_{n-1}$ and $\vec{h}_n$ are the tangent basis vectors of the axis of the segments, pointed towards the positive direction of the current; $\vec{E}_m$ is the density of the electric field at the integration point, created by the $m$th true dipole.

Introducing $N$ test dipoles, we get a system of $N$ linear algebraic equations with $N$ unknowns $I_n$:

$$[V] = [Z][I], \tag{12}$$

where $[V]$ is a column vector, containing the voltages of the sources for "true" and "test" dipoles; $[Z]$ is the matrix of mutual resistances of "true" and "test" dipoles; $[I]$ is a column vector, containing the complex amplitudes of the basis functions used to approximate the current function.

The method described is analogous to the well-known method of analysis of wire antennas by Richmond [6–7].

Finally, to find the unknown current distribution along the antenna, one needs to:

1) Separate the antenna into electrically short segments to designate the dipoles;

2) Using formula (11), find the mutual impedance of the true and test dipoles;

3) Solve the system of equations (12).

The antenna is separated into dipoles in the following way [8]. Along each dipole, a sinusoidal distribution of current is used, which is characterized by zero value of current on the ends of the dipole and peak value in the middle. Then to achieve a smooth distribution of current along the whole

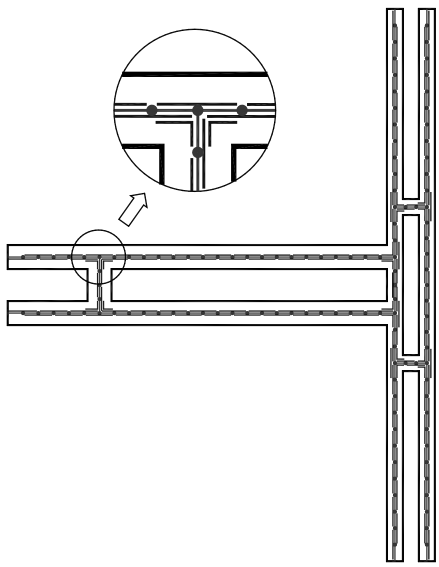


**Fig. 4. Separating the conductors of the wideband dipole antenna into dipoles**

conductor it is necessary to place the dipoles in such a way that the current is equal to zero only at the conductor's endpoints. This can be achieved by overlapping the dipoles, when one of the arms of a dipole is also an arm of a neighbouring one (Fig. 4).

Solving the system of equations, one can find the approximate distribution of the current along the antenna under consideration. Given the current distribution, one can find the input resistance of the antenna, the antenna's polar pattern and amplification factor [9–11].

**5. The Antenna's Characteristics**

The relationship between the frequency and the real and imaginary parts of the antenna's impedance is plotted in Fig. 5. One can see from Fig. 5 that the imaginary part of the impedance varies within the range of ±10 Ohms. The real part is equal to the wave impedance of the feeder (75 Ohms) at two frequencies, it changes smoothly in their neighbourhood. At the maximum point, the deviation of the real part of the impedance from 75 Ohms is +8 Ohms. Outside of the range of working frequencies both the real and the imaginary parts quickly deviate from optimal values, which explains the steepness of the left and right parts of the graph of the dependence of VSWR on the frequency.

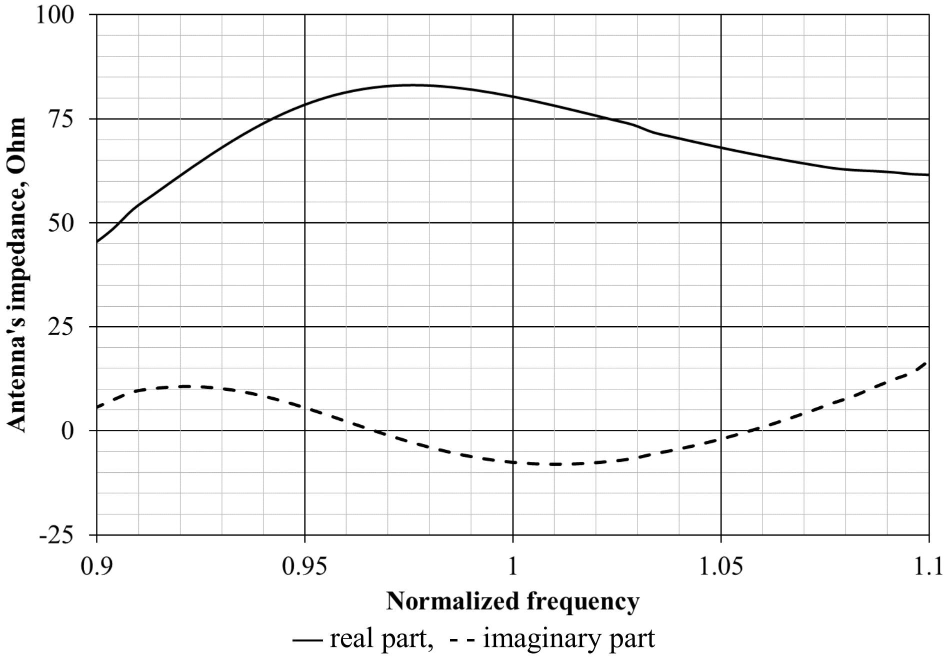



**Fig. 5. The relationship between frequency and the antenna's impedance, using a feeder with wave impedance equal to 75 Ohms**

Fig. 6 depicts the relationship between frequency and the matching between the antenna and a feeder with wave impedance of 75 Ohms (the blue line). This relationship is characterized by a long interval of VSWR below 1.15, outside of which VSWR goes up rather quickly. Then the working frequency range of the wideband antenna in question is 13 %.

In the area corresponding to the left tail of the relationship of VSWR to frequency, the real part of the antenna's impedance deviates from the optimal value much more than its imaginary part. This means that at low frequencies the changes in VSWR are driven by the real part of the antenna's impedance. In the high-frequency range the VSWR is driven by the changes in the imaginary part of the impedance, which deviates from zero much more than the real part does from 75 Ohms.

For comparison we provide in Fig. 6, a graph of the relationship between VSWR and the frequency of a single half-wave dipole (dashed line) with the same length and diameter as the wideband dipole antenna. VSWR has a single minimum, equal to 1.03, which corresponds to the resonance frequency. On the level of VSWR = 1.15 the range of matching frequencies of a single dipole is 2.9 % of the average frequency. Therefore, as a result of adding an extra closely positioned dipole, as well as other elements of the antenna, the working frequency range of the antenna expands and shifts into mostly low-frequency range.

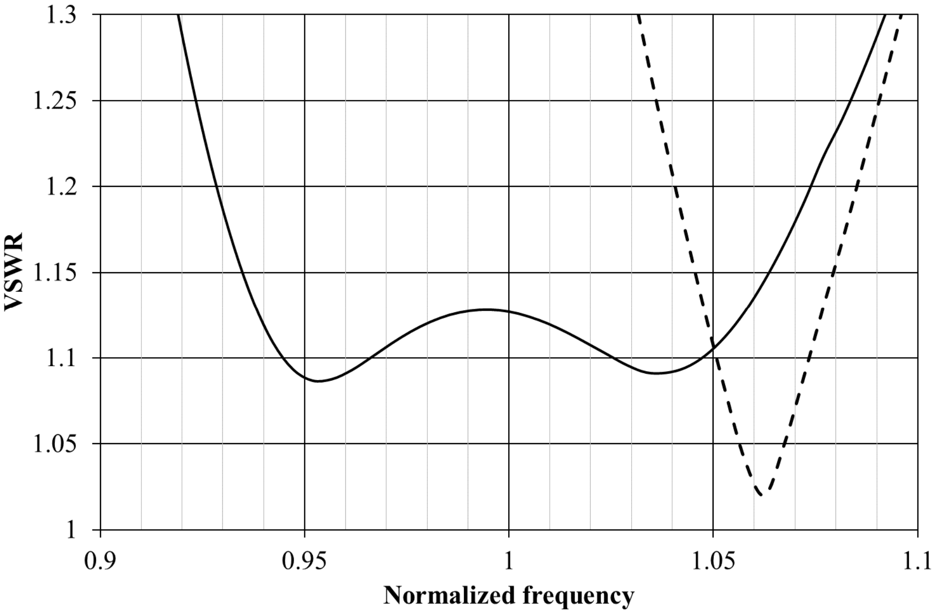



**Fig. 6. The relationship between VSWR and the frequency of the wideband dipole antenna (continuous line) and a half-wave dipole (dashed line)**

During the studies of the effects of the geometric size of the antenna on its impedance, it was discovered that the real part of the impedance in some cases reaches values close to 50 Ohms. This speaks of the possibility to match this antenna with a feeder with wave impedance equal to 50 Ohms. The most interesting results can be achieved by increasing the diameter of the dipoles and the short-circuiters: the active part of the impedance decreases for average frequencies, but increases in the high and low frequency range. Then the active part of the impedance of the antenna facilitates better matching with the feeder in a wide range of frequencies. Selecting the appropriate length of the matching piece of feeder, it is possible to make the imaginary part of the impedance of the antenna equal to zero.

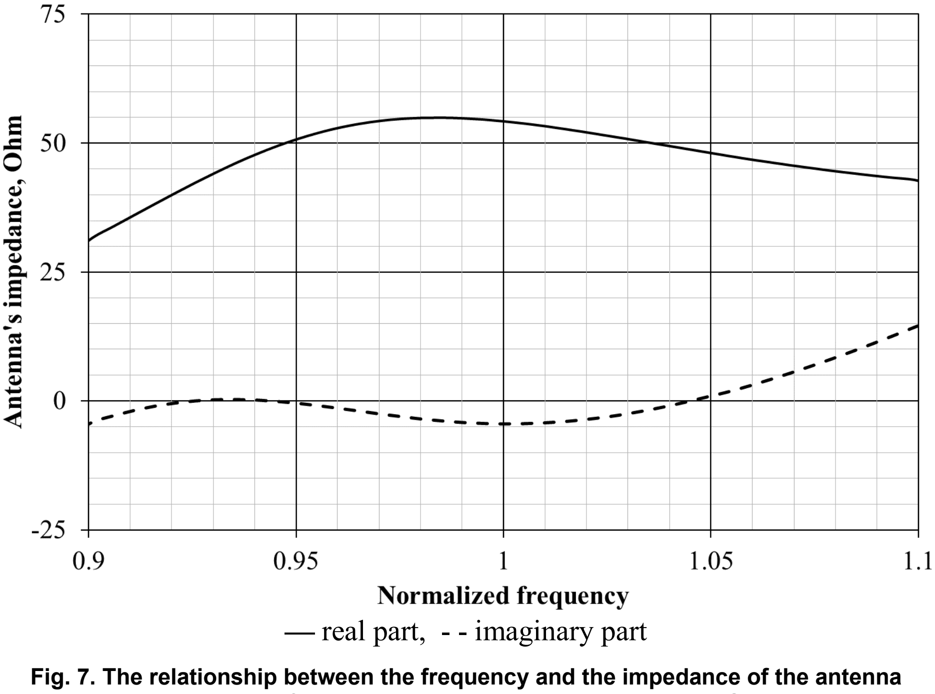



**Fig. 7. The relationship between the frequency and the impedance of the antenna matched to a feeder with wave impedance equal to 50 Ohms**

Fig. 7 presents the relationship between frequency and the antenna's impedance. The real part of the antenna's impedance is equal to 50 Ohms at two frequencies. The maximum of the real part deviates from the optimal value by 4 Ohms. The imaginary part of the antenna's impedance is equal to zero at three frequencies. The deviation of the imaginary part of the antenna's impedance from zero is within the range of ±5 Ohms.

Fig.8 depicts the relationship between VSWR and frequency when the antenna is matched with a 50 Ohms feeder. At the level of VSWR = 1.15 the working frequency range is 0.9 to 1.04, which is 15 % of the average frequency. This range is 2 % wider than the range of the 75 Ohms version of the antenna.

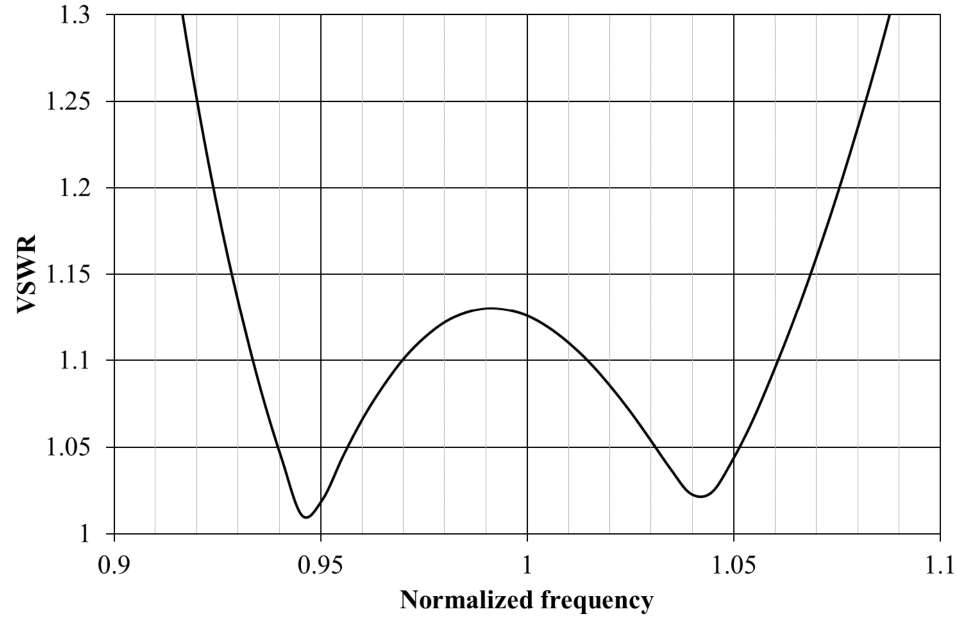
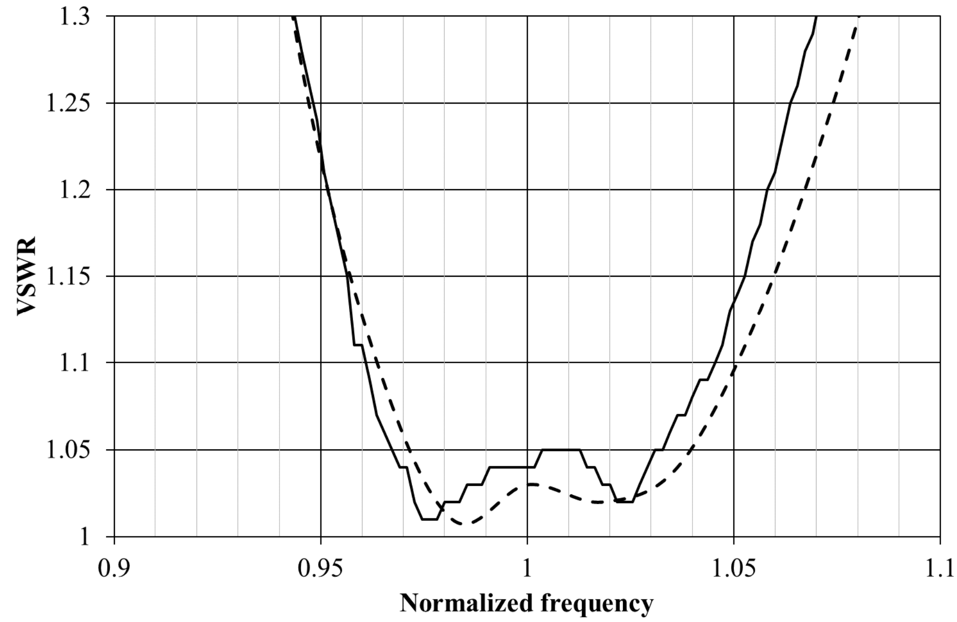



**Fig. 8. The relationship between VSWR and frequency for the antenna matched to a feeder with wave impedance equal to 50 Ohms**



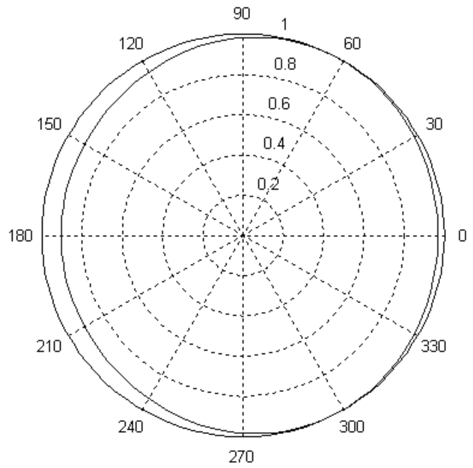

- - computed relationship, — experimental results

**Fig. 9. The relationship between VSWR and frequency**

In Fig. 9 one can see the relationship between VSWR and frequency for an antenna located above the surface of the Earth at the height equal to 2/3 of wave length. The dashed line shows the relationship computed from the numerical model; the continuous line shows the experimental data. As one can see from the graph, the computed and the experimental relationships are rather close, which can be seen as evidence that the developed physical and numerical models of the antenna describe the antenna rather well.

The antenna's polar pattern, computed at the average frequency of the working range, is shown in Fig. 10. In the plane H the diagram is close to a circle in shape. The deviation of the polar pattern from a circle is ±0.025 (0.5 dB). The deviations from a circle are observed near angles $\theta = 0°$ and $\theta = 180°$. These deviations are explained by the radiation of the short-circuiter of the balancing device.

The antenna's polar pattern in the plane E is eight-shaped. The antenna's polar pattern's behavior in the plane E is analogous to the behavior of the polar pattern of a usual half-wave dipole's polar pattern in this plane. The two differences are that first, the maxima are different and second, one can see some radiation in the direction of the dipole's axis. The non-zero level of radiation in the direction of the axis of the dipoles is due to the radiation from the balancing device. Given the data, the fractional polar pattern of the balancing device has a maximum around – 20 dB.

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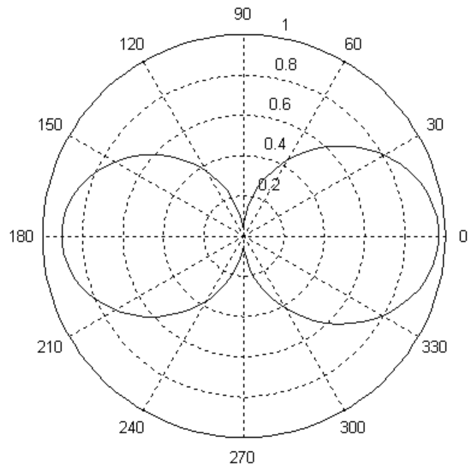


**б)**

**Fig. 10. The polar pattern of the wideband dipole antenna: a) in the H plane; b) in the E plane**

From the spatial polar pattern (Fig. 11) one can see that the field, created by the antenna's radiation is toroidal in shape, similarly to a half-wave dipole.

The antenna's directivity is equal to 2.5 dBi (0.35 dBd).

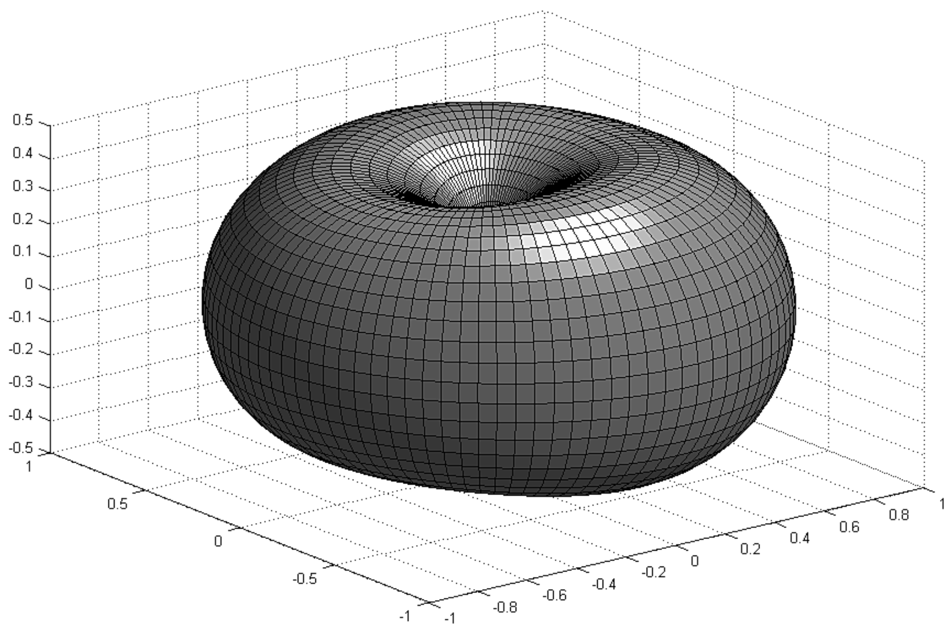


**Fig. 11. The spatial polar pattern of the antenna**

**6. Application**

A four-storied antenna array is installed on a radio and TV broadcast tower in Chelyabinsk, Russia. The array consists of 16 wideband dipole antennas, working in frequencies between 94 and 108 MHz (Fig. 12) [12–13]. It provides a gain factor of 8 dB; 10 radiostations with a total power of 16 kWt use the antenna simultaneously.

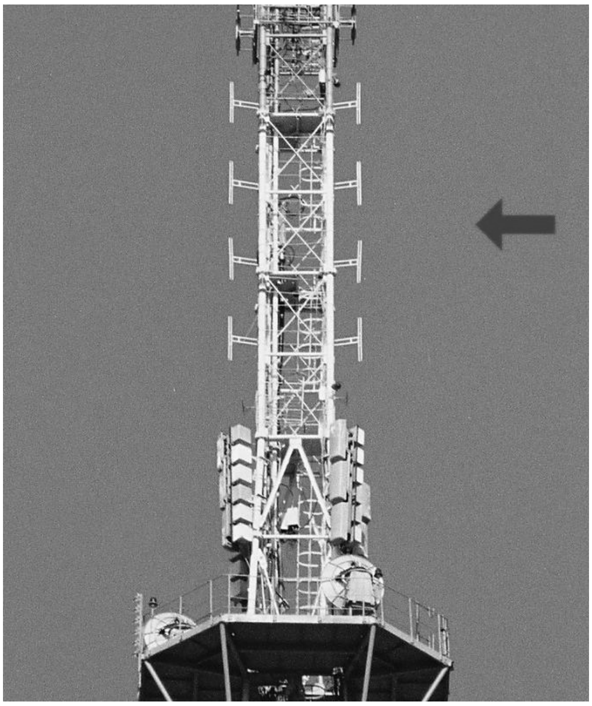

**Fig. 12. The antenna array on a television tower, consisting of 16 wideband dipole antennas (only 8 are visible in the picture)**

**Conclusion**

A new useful dipole antenna has been created. This antenna provides signal in a broad range of frequencies and therefore solves the problem of the introduction of new radio and television stations and stations connecting to mobile objects.

A methodology for parametric synthesis of the antenna has been developed. It was shown that the antenna depending on its geometric size can be matched to a feeder with predetermined wave impedance, including those with wave impedance equal to 75 or 50 Ohms.

The antenna provides:

– a symmetric polar pattern in the E plane (without the diagram being bifurcated and without the maximum of the polar pattern deviating from the plane perpendicular to the antenna's dipoles);

– a circular polar pattern in the H plane;

– a low VSWR in the power line due to matching of the input impedance of the antenna with the wave impedance of the feeder in a broad range of frequencies;

– easy installation on a belt of the lattice tower.

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# ШИРОКОПОЛОСНАЯ ВИБРАТОРНАЯ АНТЕННА

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Представлена оригинальная вибраторная антенна с КСВ ниже 1,15 в полосе частот, составляющей 13 % относительно средней частоты. В статье найдено на основе леммы Лоренца решение краевой электродинамической задачи, представлены принципы построения математической и численной моделей антенны. Приведены закономерности поведения активной и реактивной частей входного сопротивления антенны и коэффициента стоячей волны (КСВ) в фидере в диапазоне частот, особенности диаграммы направленности антенны. Показано хорошее совпадение экспериментальных данных с расчётными данными, полученными с использованием численной модели. Указано, что антенна характеризуется компактностью, механической прочностью, малым сопротивлением воздушному потоку. Антенна может быть выполнена как в трубчатом, так и в микрополосковом исполнении, при этом возможно обеспечение согласования антенны с фидером с заданным волновым сопротивлением: 50 Ом, 75 Ом или другим.

*Ключевые слова: широкополосная антенна, вибраторная антенна, радиовещание, тонкопроволочное приближение, компенсация импеданса.*

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