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INFLUENCE OF APERTURE OF RADIATING STRIP STRUCTURE ON ELECTRODYNAMIC CHARACTERISTICS OF PATCH ANTENNA

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The paper presents the results of numerical modeling of the electrodynamic characteristics of a Vivaldi type patch antenna based on a circular disk resonator. The modeling was carried out using the semi-open resonator model by the finite element method (FEM) implemented in the HFFS package. The antenna was fed using a coplanar line segment. The antenna elements were placed over a grounded plane. The influence of design parameters and the function determining the curvature of the exponentially expanding slot discontinuity on the frequency, energy and polarization characteristics was investigated. It was established that with a certain selection of variable parameters, such an antenna can be matched with external circuits in the range from 7.03 GHz to 20 GHz with a level of VSWR values not exceeding 1.92. In the amplitude-frequency characteristic, fairly wide frequency bands with almost perfect matching are observed. The choice of the type of excitation element in the form of a section of the coplanar line made it possible to exclude additional elements inherent in Vivaldi antennas, namely, a section of the auxiliary strip line and a balancing resonator. This kind of antenna allows to form radiation patterns of various shapes from single-sided to cosecant quadrate. At the same time, in some intervals of observation angles, the formed fields turn out to be elliptically polarized with an ellipticity coefficient close to unity. The combination of the obtained results makes it possible to predict the use of this kind of antennas for operation with broadband signals.
Keywords: *Ring resonator; Antenna Vivaldi; Coplanar line; Matching; Frequency characteristics; Energy characteristics*
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Small-size strip-type antennas with various radiating apertures have long been an integral part of radio engineering systems for various purposes. The bibliography, which reflects possible variants of aperture, can be found in a large number of publications [1-3]. The purpose of this or that type of aperture is determined by the need to solve certain radio engineering problems. If such a single antenna had to have a maximum (or very high compared to an isotropic radiator) gain, the designs described in [4, 5] were used. If it was necessary to be able to operate with arbitrary polarization of the radiated or received fields, other designs were used [6, 7]. Structural (topological) solutions for both one and another case have both general principles of construction of structures and presence of elements, which lead to fundamental differences both in circuit solutions and in approaches, methods of modeling and determination of parameters of such complex-composition systems [8].

A special place is occupied by planar single antennas (or antenna arrays based on them), which are used for transmission (reception) of ultra-wideband signals. Such kind of radiating structures should have as significantly wider operating band (or several separate bands) in comparison with "standard" technical solutions, acceptable gain and acceptable level of matching with external circuits. Quite a large number of designs and technical solutions are known that satisfy such requirements [9-11]. In addition, there are a number of other factors (e.g., antenna location in space) that can significantly complicate the application of known designs or require their substantial modernization.

One of the most important elements of any microwave design is the element of feeding (in fact, the method of feeding) of a certain (given) spectrum of oscillations. Among the most widespread methods of feeding in the microwave range we can point out the planar ones - it is feeding by means of sections of various types of strip lines [12], sections of coaxial line [13], and in the high-frequency part of the microwave range (above 20 GHz) - sections of standard metal or dielectric waveguides [14].

Any of the known feeding methods has both known advantages and disadvantages. For example, the planar method of feeding allows to preserve the overall planarity of the structure. At the same time, taking into account the possibility of existence of higher types of waves (under certain conditions), the process of simulation the parameters of such a structure becomes much more complicated. When using multi-element stripline systems for feeding (for example, coplanar or multiconductor), it is necessary to take into account a wide enough spectrum of possible natural waves. The use of the feeding method using a coaxial line segment basically violates the planarity of the structure. In addition, under certain conditions, this method of feeding can lead to the need to search for non-standard design solutions. At the same time, due to the peculiarities of the coaxial line itself, the spectrum of the considered natural waves existing in the radiating structure is limited in the low-frequency part when modeling the characteristics.

Considering all these factors, it is relevant to study the influence of the radiating aperture of a planar antenna on its characteristics at a given method of feeding.

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In this paper we consider an antenna with an exponentially varying aperture opening (Vivaldi type antenna) and the effect of different parameters on the frequency, energy and polarization characteristics of the antenna.

STRUCTURE UNDER STUDY

We will consider an electrodynamic structure, which is a disk-strip resonator having an exponentially expanding slot. Antennas with this kind of slot inhomogeneity are called "Vivaldi antennas" in the known literature [15, 16]. A disk-shaped strip resonator, or patch resonator, is placed on a thin dielectric substrate. This entire structure is placed over an infinitely extended, infinitely conducting metallic plane (Fig. 1). It should be noted that such an electrodynamic model is as close as possible to real antenna designs for various purposes. In Fig. 1 the following designations are used: 1 - metallic plane, 2 - dielectric substrate, 3 - patch element, 4 - coplanar line elements.

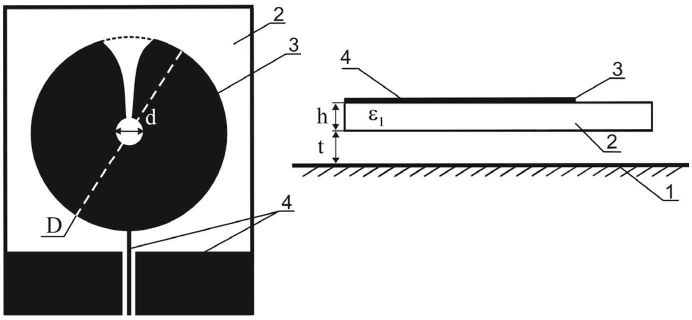

Figure 1. The structure geometry and notations

In known designs, feeding of the slot discontinuity is carried out by means of a strip line segment located under the slot discontinuity. A symmetrizing strip resonator is an obligatory element. All this complicates the design and affects the antenna characteristics quite strongly. In the proposed design, the feeding is carried out using a disk slot discontinuity. Due to the fact that this discontinuity feeds axially symmetric types of oscillations (due to a certain choice of geometric dimensions of the structure in comparison to the resonant frequencies), there is no need to use an auxiliary strip resonator, in addition, all elements of the structure are located in one plane.

Geometric dimensions and material constants were chosen based on the assumption that the antenna is designed to operate in the microwave frequency range. The following values of parameters were chosen: external diameter of the patch element $D = 13.5$ mm; internal diameter $d = 2$ mm; thickness of dielectric substrate $h = 0.5$ mm; the values ε, t are variant values. The infinity of the dimensions of the metal plane allows not to take into account the edge diffraction effects.

RESULTS OF NUMERICAL SIMULATION

The construction of a rigorous electrodynamic model of such a structure is rather difficult and, as it seems, practically impossible in the near future. Numerical simulation can be realized within the framework of the well-known model of a semi-open resonator. The model assumes, the resonator is formed by two elements – a patch element and a grounded base. Under the assumption that the metal of the elements is ideal, the classical boundary condition of zero equality of the tangential component of the electric field is satisfied on the elements. Another element of the resonator is the cylindrical surface, which is defined by the projection of the patch element onto the grounded plane. The magnetic wall condition is satisfied on this surface.

Based on the chosen ratio of the structure parameters and imposing certain restrictions on the parameter t, we can say that if the thickness of the dielectric substrate and the distance to the grounded base are significantly smaller than the resonant length in the resonator λ_r, the electric field vector will not have variations along the coordinate system ort perpendicular to the plane of the structure. In this case, the spectrum of oscillations excited in the resonator will include only oscillations of the E_{mn0} (TM_{mn0}) type.

Numerical simulations have been carried out using the finite element method (FEM) implemented within the commercial ANSOFT HFFS package [17]. As it is obvious, the dependencies of the main frequency and energy parameters are multi-parametric. For this reason, a multi-criteria optimization was carried out, first of all, of the return loss value $|S_{11}|$ using the above-mentioned variational parameters.

As it is known, the return loss value $|S_{11}|$ and the associated VSWR (voltage standing wave ratio) value determine the degree of matching of the device with external circuits. This parameter is important both from the point of view of minimal impact on the source that excites oscillations, and from the point of view of effective transfer of oscillation energy to the final device. The dependencies of both quantities are multi-parametric on the antenna geometric dimensions and material constants. For this reason, the evaluation of the matching level by only one parameter is not an absolute criterion for the overall performance. Nevertheless, the study of partial dependencies of return loss on any of the parameters allows us to determine the frequency bands within which effective operation is possible (in this case, it is effective radiation).

Analysis of known designs using strip, microstrip, slot and coplanar structures shows that an integral part is a dielectric substrate, on which the patch elements are placed. The dielectric substrate is thus an important structural element, but, at the same time, the substrate is involved in the formation of a certain field structure, affecting the value of the input impedance (i.e., affecting the value of the matching of the device as a whole). Thus, the substrate parameters thickness h and dielectric constant value ε_r are important parameters. Moreover, the dielectric substrate thickness is a decisive factor for eliminating the possibility of excitation of surface waves in the dielectric substrate. In this regard, a priori the substrate thickness h is chosen "thin" in comparison with the resonance lengths of oscillations that are excited in the structure, and in comparison, with the operating wavelength ($h << \lambda_r$, $h << \lambda$). We limit the operating frequency range to the value of $F = 20$ GHz, because above this frequency, higher types of waves and slot waves may exist in the feed coplanar line. The value of the thinness is chosen to be $h = 0.5$ mm, which is significantly smaller than the minimum operating wavelength $\lambda = 1.5$ cm for the $F = 20$ GHz frequency.

Fig. 2 shows the dependences of the return loss value $|S_{11}|$ in a given frequency range when the dielectric constant of the substrate varies. Values of dielectric permittivity are chosen from a number of values that are used in real devices.

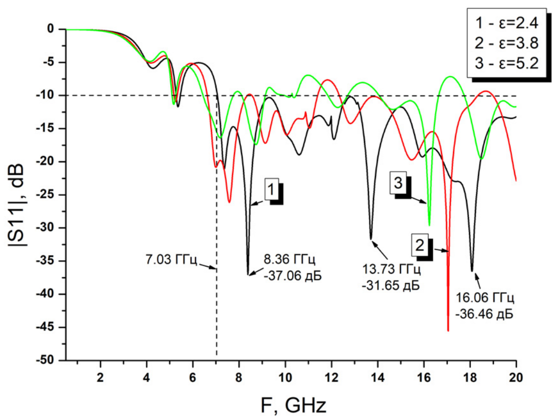

Figure 2. Dependencies of $|S_{11}|$ vs frequency with ε_r variation

The analysis of dependencies shows that all dependencies have oscillatory character regardless of the value of ε_r. The frequency range (from 0.5 to 3 GHz) is clearly seen, within which a complete reflection is observed, i.e., matching is not possible in principle. In the vicinity of 5 GHz, a not wide local band with an acceptable level of return loss is observed. For the dielectric substrate with the value of $\varepsilon_r = 2.4$, starting from the $F = 7.03$ GHz frequency, an ultra-wide band opens up with a broadband coefficient of $\xi \approx 2.84$. This value of ε_r should be considered optimal. And, although within this band there are certain oscillations of the value of $|S_{11}|$, the absolute level of return loss does not exceed the value of -10 dB (corresponding to the value of VSWR $\approx$ 1.92). In addition, near the frequencies 8.36 GHz, 13.73 GHz, 16.06 GHz local frequency bands are observed, within which there is almost perfect matching with a level less than - 30 dB, which corresponds to VSWR < 1.06 and direct losses of -0.004 dB. Near these frequencies, the effective radiation pattern of the antenna can be predicted. However, other antenna characteristics may not have maximum values at other frequencies in the range of return loss levels less than -10 dB.

Another important antenna design parameter is the parameter t. It is the distance from the patch element to the ground plane. From the point of view of electrodynamics, this parameter is important for two reasons. First, it determines the size of the region where the energy of excited oscillations is concentrated. Second, this parameter will ultimately influence the value of the resonant frequency of the structure. And thus, the combination of these two factors will determine on the energy characteristics of the antenna (gain, pattern, polarization characteristics).

Fig. 3 shows the dependence $|S_{11}|$ vs the frequency with variation of the parameter t.

The analysis of the above dependences shows that in the considered frequency range all dependences have a sharply oscillatory character. Especially noticeable are the drops of $|S_{11}|$ values at a small value of the parameter t ($t = 1.5$ mm, curve 1). This is explained by the factor that at close location of the screen to the coplanar line elements it passes from the class of isolated coplanar lines to the class of grounded coplanar lines, which are characterized by a strong dispersion dependence. Increasing this distance leads to a decrease in this dependence, while a decrease in ripples is observed.

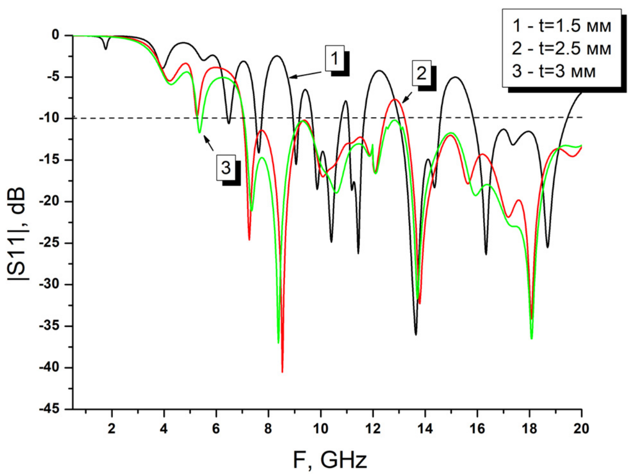

Figure 3. Dependencies of $|S_{11}|$ vs frequency with variation t

By using the optimization procedure, a value of the parameter $t=3$ mm (curve 3) is obtained at which the ripple of $|S_{11}|$ does not exceed the value of -10 dB. Further increase of the parameter t does not lead to reduction of the ripple level, and from the structural point of view the structure itself loses one of its main advantages it is planarity.

The classical version of the Vivaldi type strip antenna for excitation involves the use of a strip line segment with a symmetric resonator. The functional purpose of the symmetric resonator is to equalize the phases of the currents flowing along opposite sections of the slot discontinuity. The option of using for such an antenna actually a ring resonator allows to simplify the design considerably. Fig. 4 shows the distribution of current density lines on the disk patch element and the ground plane.

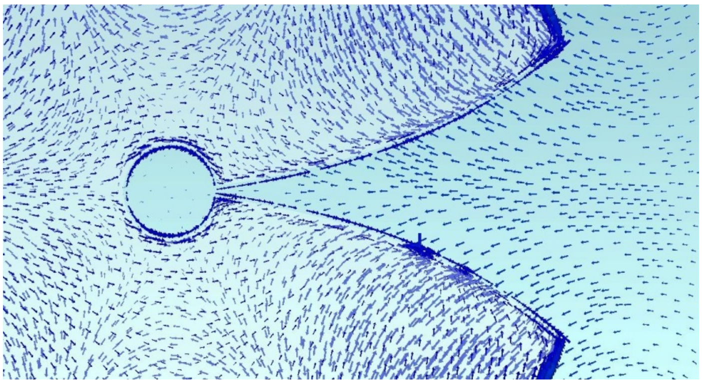

Figure 4. Structure of current density lines on the antenna elements

The image analysis shows that the internal slot resonator is excited on one of the lowest axially symmetric oscillation type E_{020}. And the currents that come to the beginning of the exponential slot discontinuity come in the same phase. For this reason, it can be assumed that the radiation pattern will have a single-lobe shape. The currents on the ground plane are in anti-phase with respect to the currents on the patch element.

The topology of the exponential slot discontinuity (actually the opening angle) has a significant influence not only on the magnitude of $|S_{11}|$, but also determines the antenna gain. Fig. 5 shows two dependences of the gain on frequency for two different topologies defined by the functions: curve 1 - $2\cdot\exp(-0.3\cdot x)+0.1$; curve 2 - $8\cdot\exp(-0.123\cdot x)-1$ for the optimized value of the parameter $t=3$ mm and the value of the relative dielectric constant of the substrate $\varepsilon_r=2.4$. x is a linear coordinate along the exponential slot. The gain dependencies are plotted with respect to the gain of an isotropic radiator (IEEE classification in dBi).

As it is obvious both dependences have oscillatory character. However, in the case of a larger opening (curve 2) the scatter of values is smaller and amounts $\approx 34\%$ to 6.67 dBi from the mean value compared to a smaller opening where the scatter amounts $\approx 47\%$ to 6.16 dBi from the mean value. Both dependencies have an absolute maximum, but these maxima are quite strongly shifted in frequency relative to each other. These maxima are much higher than the "standard" value of patch antenna gain (in general it is 5...6). But, if in known designs such values are achieved only at some fixed frequencies (in some cases in the band of 1...2% reduced to the center frequency of this range), then, focusing on the value of 6 dBi, the band in this case is $\Delta F=6.8$ GHz (reduced to the center frequency - 86%). That is, in this band it is possible to work with wideband signals.

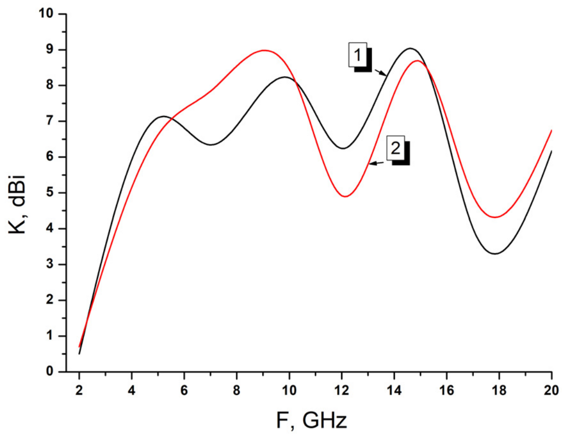

Figure 5. Dependences of the gain coefficient vs frequency at variation of the slot discontinuity opening function

Since the energy and polarization characteristics are multi-parametric dependencies, it is possible to synthesize antennas with given parameters using various optimization procedures. As an example, in Fig. 6 one can find the normalized radiation patterns in the azimuthal plane (as with any traveling wave antenna) at two frequencies $F = 7$ GHz and $F = 8.38$ GHz for an antenna with optimized values of the parameters ε_r and t. The frequencies are chosen based on the specific use of the antenna. These two frequencies correspond to two minima in the low-frequency part of the considered range near the minima of the $|S_{11}|$ function values.

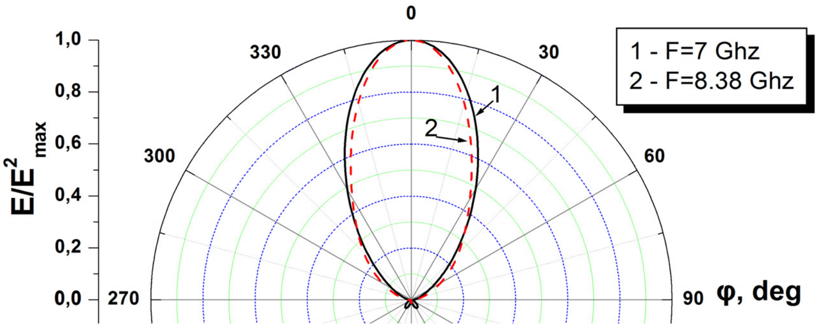

Figure 6. Directional patterns in azimuthal plane with optimized set of parameters

It is obvious that at both frequencies the directivity patterns are single-lobe, symmetric with respect to the direction of the axis of the exponential slot inhomogeneity, the maximum of the main lobe of the pattern is observed in the direction of this axis. The level of the rear lobes at the $F = 7$ GHz frequency does not exceed -18 dB. The width of the diagram at 0.707 level depends on the topology of the slot heterogeneity (actually the maximum opening), which is determined by the curvature change function. In this case, the diagram is given for the function (wide opening) and the width is 35^0. By varying the parameters t, ε_r and the curvature change function, it is possible to form directional diagrams of other shapes (double-lobe, cosecant quadrate, etc.).

In most cases, planar patch antennas form linearly polarized radiated fields, unless the design uses various auxiliary elements that change the distribution of surface currents on the surface of the patch elements (e.g., short-circuits), or uses multiport feeding with a certain phase shift. In the antenna under consideration, over the entire operating frequency range, relatively narrow intervals of angles are observed within which elliptical polarization of the radiated fields can be obtained. These frequencies are usually coincident (or very close) to the natural resonant frequencies of the types of oscillations excited in the resonating volume. However, at some frequencies in the antenna without using known techniques it is possible to obtain radiated fields elliptically polarized with an ellipticity coefficient close to zero (according to the IEEE criterion in dB). Fig. 7 shows the angular-local polarization characteristic of the antenna at $F = 8.38$ GHz. Near this frequency, a rather deep minimum with a level up to -37 dB is observed on the amplitude-frequency characteristics (with parameter variation t, ε_r) (the VSWR level of 1.029 and direct loss of -0.001 dB are provided).

As one can see from the graph above, in the range of observation angles from 78.5^0 to 109.9^0 the ellipticity coefficient does not exceed the value of 3 dB, i.e. polarization is close to circular. At the observation angle $\theta = 91.85^{\circ}$ the value of the ellipticity coefficient is $\eta = 0.053$ dB. In other ranges of angle variation, linear polarization is observed. By varying the parameters ε_r and t the opening angle, the ellipticity coefficient can be achieved, but other important characteristics can be significantly degraded.

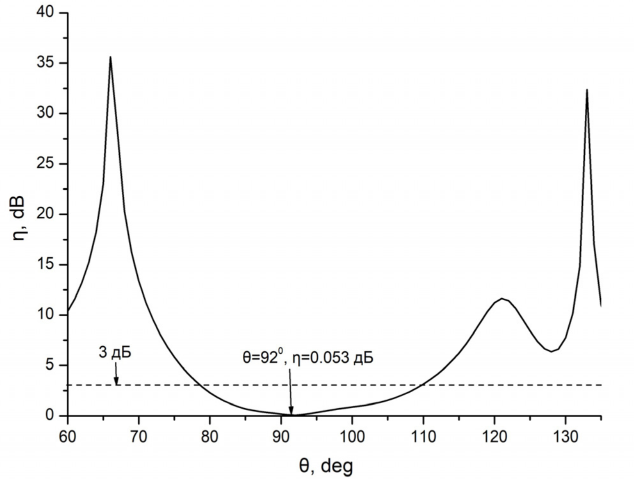

Figure 7. Polarization characteristic at the $F = 8.38$ GHz frequency

CONCLUSION

The paper presents the results of numerical modeling of the parameters of the Vivaldi type patch antenna. The antenna excitation was carried out by means of a coplanar line segment. The antenna and exciter elements were placed on a dielectric substrate and were "suspended" above a grounded base. The presence of a sufficiently large number of variable parameters allows control of frequency, energy and polarization parameters in a sufficiently wide frequency band. The antenna is sufficiently well matched with external circuits in a wide enough frequency range and has a sufficiently high gain in comparison with known designs based on various planar structures. The totality of the obtained results allows us to predict the use of this kind of antennas for operation with broadband signals.

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ВПЛИВ АПЕРТУРИ ВИПРОМІЮЧОЇ СМУЖКОВОЇ СТРУКТУРИ НА ЕЛЕКТРОДИНАМІЧНІ ХАРАКТЕРИСТИКИ ПАТЧ АНТЕНИ

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У статті представлено результати чисельного моделювання електродинамічних характеристик патч-антени типу Вівальді на основі кільцевого дискового резонатора. Моделювання здійснено з використанням моделі напіввідкритого резонатора методом кінцевих елементів (МКЕ), реалізованого в пакеті ANSOFT HFSS. Збудження антени здійснювалося за допомогою відрізка копланарної лінії. Елементи антени розміщувалися над заземленою площиною. Досліджено вплив конструктивних параметрів і функції, що визначає кривизну щілинної неоднорідності, яка експоненціально розширюється, на частотні, енергетичні та поляризаційні характеристики. Встановлено, що за певного вибору варіативних параметрів таку антену вдається узгодити із зовнішніми ланцюгами в діапазоні від 7.03 ГГц до 20 ГГц з рівнем значень КСВН, що не перевищують величину 1.92. В амплітудно-частотної характеристиці спостерігаються досить широкі частотні смуги з практично ідеальним узгодженням. Вибір типу елемента збудження у вигляді відрізка копланарної лінії дозволив виключити додаткові елементи, притаманні антенам типу Вівальді, а саме, відрізок допоміжної смужкової лінії та симетруючий резонатор. Такого роду антена дозволяє формувати діаграми спрямованості різної форми від однопелюсткової до косеканс квадратної. При цьому в деяких інтервалах кутів спостереження поля, що формуються, виявляються еліптично поляризованими з коефіцієнтом еліптичності близьким до одиниці. Сукупність отриманих результатів дозволяє прогнозувати використання такого роду антен для роботи з широкосмуговими сигналами.

Ключові слова: *кільцевий резонатор; антена Вівальді; копланарна лінія; узгодження; частотні характеристики; енергетичні характеристики*