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ANTENNA BASED ON COMPLICATED COPLANAR STRUCTURE

Sergey A. Pogarsky*, Dmitry V. Mayboroda, Serhii M. Mykhaliuk
V.N. Karazin Kharkiv National University, 4, Svobody Sq., Kharkiv, Ukraine, 61022
**Corresponding Author e-mail: spogarsky@gmail.com*
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This paper presents the results of a numerical study of a planar antenna with a complex form factor. The antenna is based on a combination of two resonators, a disc resonator and a ring resonator. The feeding of the ring resonator is performed using a coplanar structure: pointwise by galvanic contact between the central conductor of the coplanar line and the ring resonator and by distributed electromagnetic coupling of the ring resonator and the aperture of the outer conductor of the coplanar line. The antenna was placed over a metal plane whose geometric dimensions were significantly larger than those of the antenna to exclude the influence of edge diffraction effects. In numerical simulation a complex approach including the method of semi-open resonator and the finite element method (FEM) implemented within the commercial package HFFS was used. The dependences of spectral, energy and polarization characteristics on material constants and frequency parameter have been investigated. It was found that within the framework of single-parameter optimization it is impossible to simultaneously achieve a high level of all important parameters. The values of frequencies of spectral lines in the spectral characteristics of the antenna are found with a relative error not worse than 1200 Hz. Frequency ranges within which there is no degeneration of oscillation types are established. The distributions of surface currents on the metal elements of the antenna, allowing to determine the position of phase centers of excitation, are presented. It is shown that the proposed antenna can provide an acceptable level of matching both at fixed frequencies and in sufficiently wide local frequency bands, reaching 11% with respect to the center frequency of the sub-band. The boundary values of gain coefficients in frequency bands are established. The simulation results allow to predict effective radiation with formation of practically single-lobe radiation pattern and presence of elliptical polarization.
Keywords*: Ring resonator; Disc resonator; Coplanar line; Matching; Frequency characteristics; Energy characteristics*
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Since the mid-50s of the last century, functional devices based on strip (microstrip) structures have occupied a dominant position in the creation of complex radio engineering systems, especially if one of the main conditions is the condition of miniaturization. Here we can point out numerous designs of filters, directional couplers, mixers, power dividers, antennas, and recently - frequency selective surfaces, etc. [1-7]. A special place among all these technical solutions is occupied by the structures having in their composition structures with axial symmetry - these are disc and ring microstrip elements. This is due to the presence of peculiarities of electrodynamic properties of such structures. The main of which are related to the presence in such structures of degenerate types of waves (or types of oscillations in those cases when we are talking about resonators based on them), the effect of coupling between these oscillations and the possibility of influencing the level of coupling, the possibility of removing degeneration, due to which there is a possibility of controlling the operating bandwidth and some others.

The first attempts of practical use of ring structures were made to measure the phase velocity and dispersion characteristics of microstrip lines (P. Troughton [8]). Later, axially symmetric structures found their application in the creation of various functional elements and devices. Such intensive use of these structures caused the necessity to create mathematical models to describe and predict these or those characteristics. To date, quite a large number of approaches, models for analyzing the parameters of axially symmetric structures are known. Most of these models are focused on finding only resonance frequencies of excited types of oscillations. Exhaustive information on the parameters of structures is provided by the so-called full-wave models. Such models are quite complex in themselves and encounter certain difficulties in their practical use. For express calculations simplified models are usually used, for example, using the method of circuits, allowing to calculate parameters of inhomogeneous circuits and circuits with local inhomogeneities [9]. In 1971, the so-called "magnetic wall model" for microstrip resonators based on axially symmetric structures was proposed (sometimes another name of this model is used - the model of a half-open resonator) [10]. The main idea of this method is that the boundary conditions are formulated in a special way: on the metallic surfaces of the structure it is a natural boundary condition (equality to zero of the tangential component of the electric field), and on the lateral cylindrical surfaces bounding the resonator it is a magnetic wall condition. This model has been subjected to numerous modifications using various approaches [11], which allowed us to significantly improve the accuracy of the calculations. At the same time, the semi-open resonator model does not give correct results for coupled modes and in cases with complex boundary conditions, for example, in the presence of slot inhomogeneities in a microstrip disc. The inclusion of feeding elements (sections of microstrip or coplanar lines, sections of coaxial) or auxiliary elements (short-circuits, stubs) in the design further complicates the problem of finding the eigen-resonant frequencies and other characteristics. For this reason, the best solution is to use an integrated approach based on a combination of a semi-open resonator model and some numerical method such as the finite element method (FEM).

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The aim of this work is to simulate the electrodynamic characteristics of a hybrid metal-dielectric plane structure based on a coplanar line and placed over a metallic surface.

STRUCTURE UNDER STUDY

We will consider a hybrid microstrip structure (Fig.1), which is a coupled ring and disc microstrip resonators feeding by a coplanar structure and placed above a metallic plane.

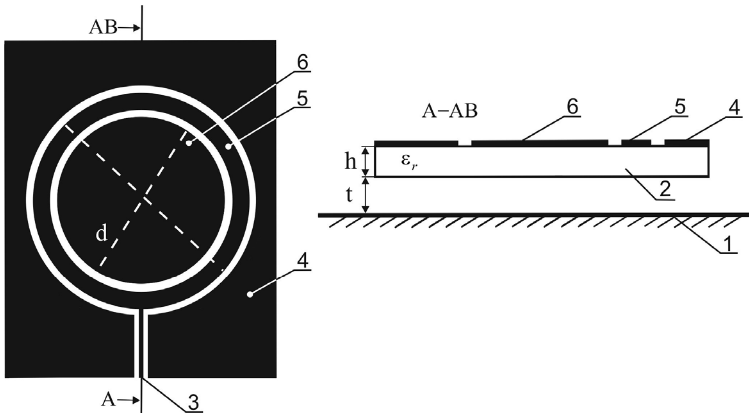


Figure 1. The structure geometry and notations

The ring and disc resonators are formed by metallized patches, respectively, and an external metallic plane. The introduction of the metallic plane is due to giving the model more generality and simulation of the antenna location in real conditions. The figure denotes are: 1 - external metal plane, 2 - dielectric substrate, 3 - inner conductor of coplanar structure, 4 - outer conductor of coplanar structure, 5 - ring patch, 6 - disc patch. There is an air gap between the dielectric substrate and the metal plane, which can be filled with additional dielectric. The simulation assumed a variation of the values of the relative dielectric permittivity of the substrate. In the limiting case the value is of $\varepsilon_r = 1$. The geometrical dimensions of the structure were chosen based on the assumption that this structure is designed for operation in the centimeter wavelength range. The outer metallized plane had finite dimensions. However, its dimensions were chosen in such a way that the geometric dimensions of the antenna elements and the resonant lengths of oscillations in the resonators were significantly smaller than the geometric dimensions of the plane (on average for the considered operating frequency range by a factor of 10). With such a ratio, one can ignore the occurrence of edge diffraction effects and the so-called "flowing" of currents effect to the opposite side of the metal plane.

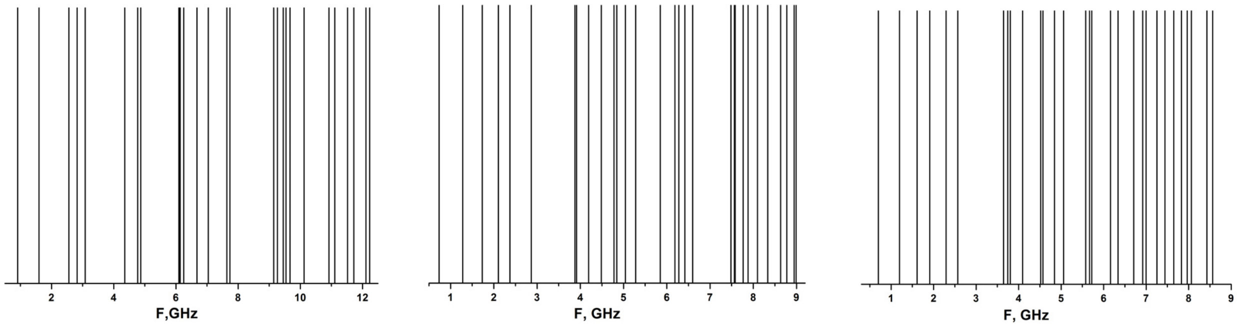
RESULTS OF NUMERICAL SIMULATION

As it is obvious, the antenna design itself is quite complicated, so it is practically impossible to talk about the construction of a rigorous model that takes into account most of the factors. In numerical simulations, a complex approach including the semi-open resonator method and the finite element method (FEM) implemented within the commercial package HFFS [12] has been used. Considering the fact that all dependencies are multi-parametric, it is necessary to optimize each dependency for all the variational parameters. Such parameters in this case were h - the thickness of the dielectric substrate, t - the value of the gap between the substrate and the metallic plane and ε_r - the value of the relative dielectric permittivity of the substrate. The diameters of the ring and disc were fixed. Their values were chosen based on the wavelengths of the operating range.

The basis of this antenna consists of two resonators, a disc and a ring resonator, and a coplanar ground plane surrounding them, which plays an essential role in the excitation of the resonators. For this reason, the first step is to investigate the spectral composition of the types of oscillations that are excited in it under the variation of the given parameters.

Based on the data obtained in the study of similar structures [13, 14], a significant influence on the spectral composition of excited oscillations has the value of the relative dielectric permittivity of the dielectric substrate and the distance to the ground plane (with fixed diameters of the resonators and fixed coupling between them at a level approaching the critical level to ensure a wider operating bandwidth). However, there is one more parameter in this design, which is the amount of gap between the outer ring resonator and the coplanar ground plane. This parameter determines the magnitude of coupling with the feeding coplanar line, the uniformity of the coupling magnitude along the perimeter of the ring resonator conductor and directly affects the antenna operating bandwidth.

Fig. 2 shows the spectral characteristics of the structure at a fixed value of the parameter $t = 2$ mm and variation of the dielectric constant of the substrate $\varepsilon_r \to \text{var}$ (1, 3.8, 5.2). Values 3.8 and 5.2 correspond to standard values, which are quite often used in practice, value 1 is the minimum limit value. In numerical simulations, an additional criterion was used - the maximum number of excited oscillations, equal to 30. And the band within which these types of oscillations are excited is a derivative value.



a) $\varepsilon_r = 1$ b) $\varepsilon_r = 3.8$ c) $\varepsilon_r = 5.2$

Figure 2. Spectral characteristics

It should be pointed out that all eigen-frequencies are determined with a relative accuracy of no worse than 10^{-7}, which corresponds to a frequency error of 1200 Hz at the widest possible frequency bandwidth considered at $\varepsilon_r = 1$, $t = 2$ mm. Extension of the considered frequency range beyond the established limits is inexpedient, because, firstly, the spectra are too dense and it is difficult to identify and analyze the structure of such oscillations, secondly, the number of degenerate types of oscillations increases, it is practically impossible to identify them with a dense spectrum, and, thirdly, extension of the frequency range leads to unreasonably large expenditures of simulation time.

The analysis of the presented characteristics shows that at a fixed value of the parameter t at the lowest value ε_r the designated 30 types of oscillations fit in the frequency range from 0.91 GHz to 12.23 GHz. Moreover, near the frequency $F = 6$ GHz, a fourfold degeneration of the oscillation types is observed, and near the frequency $F = 10.1$ GHz, a twofold degeneration is observed. As the value ε_r increases, the spectral response shifts towards lower frequencies: at the $\varepsilon_r = 3.8$ lower frequency is $F = 0.736$ GHz, and at $\varepsilon_r = 5.2$ already $F = 0.69$ GHz. At $\varepsilon_r = 3.8$ the degeneration is observed only near the frequency $F = 7.57$ GHz (twofold), and at $\varepsilon_r = 5.2$ only near the frequency $F = 6.93$ GHz (twofold). In the remaining of the frequency range, only densification of spectral lines is observed. In addition, the operating range narrows with increasing ε_r, which correlates with the presence of 30 first types of oscillations.

The characteristics presented in Fig. 2 are obtained after optimizing the spectral composition depending on the parameter t - the distance to the common ground plane. The optimal value is equal to $t = 2$ mm. Decreasing or increasing the value of this parameter does not play a significant role in terms of the emergence (or suppression) of additional resonances or manifestation of degeneracy of oscillation types. The reason is transparent - it is necessary to fulfil certain resonance conditions. In this case - it is a complex electrodynamic structure, for this reason it is impossible to formulate any definite criterion requirements for the values of the studied parameters.

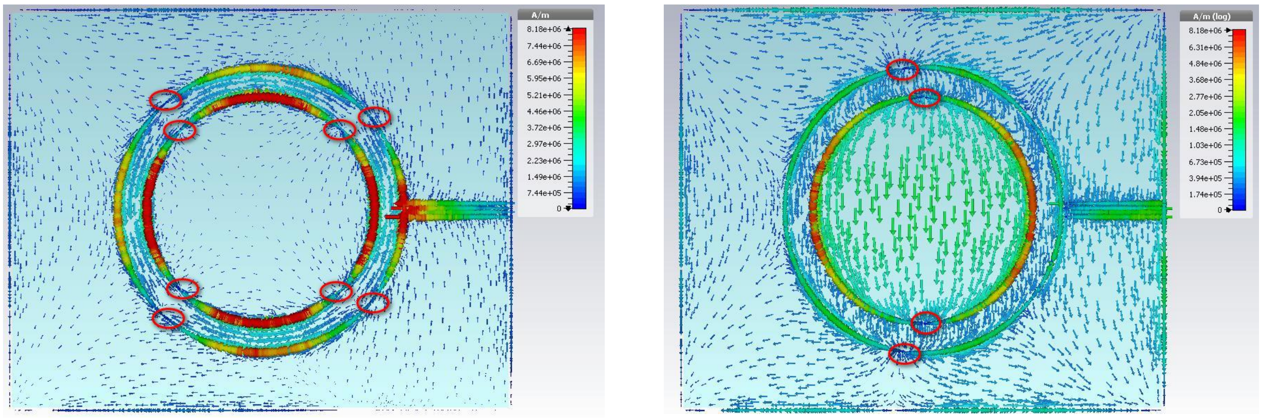
Another important parameter that has a significant influence on the antenna performance as a whole is the coupling value of the resonators and the feeding coplanar line. In most of the known designs that use the coplanar line as the feeding element, due to the simple (linear) form factor of the coplanar line, it is relatively easy to maintain a certain level of coupling between the elements of the device. In the case under consideration, maintaining a given level of coupling (and effective excitation of the antenna apertures) can be realized if it is possible to ensure the flow of surface currents across the entire surface of the outer conductor of the coplanar line. To study this issue, the simulation of surface currents distribution on all antenna elements has been carried out.

Fig. 3 shows the results of the simulation of the surface current distribution in the antenna at frequencies coinciding with the frequencies of the spectral lines for the antenna with the parameters $\varepsilon_r = 5.2$, $t = 2$ mm, the value of the gap between the coplanar line ring conductor and the ring resonator is 0.4 mm (this size provides a coupling close to critical), the outer and inner radii of the ring resonator are 17 mm and 14 mm, respectively, the radius of the disc resonator is 13.5 mm. The frequencies at which the modelling was performed: in Fig. 3a is $F = 3.815$ GHz, in Fig. 3b is $F = 4.51$ GHz.

The analysis of graphical constructions allows us to conclude that at the $F = 3.815$ GHz frequency both the ring resonator and the disc resonator are excited on the type E_{040} of oscillations. It is not possible to identify the type of oscillations that is excited in the coplanar part of the structure.

At the frequency $F = 4.51$ GHz, the phase centers of excitation of both the disk resonator and the ring resonator and the coplanar part of the structure are clearly identified (marked with ellipses in the figures). All of them are almost in-phase excited on the type E_{020} of oscillation. In addition, if we investigate the junction region of the center conductor of the coplanar line and the ring resonator, we can state that at the frequency $F = 3.815$ GHz there is a significant concentration of current density at the junction. This may indicate that the coplanar line itself and the ring resonator are to some extent not matched in terms of characteristic impedance. Conversely, a good level of matching can be expected at $F = 4.51$ GHz.

The presence of such features in the structure of current lines leads to the necessity of additional study of the antenna matching with external circuits at variation of selected parameters. The matching process is relevant for two reasons: the first is the minimum impact on the microwave oscillator, and the second is the effective radiation of the antenna. It is accepted that the level of matching is evaluated either by the return loss level or by the VSWR level. It can be argued that both of these quantities are multi-parametric dependencies on the geometric dimensions, material constants of the antenna and frequency. Therefore, optimization of the matching level by one of the parameters (practically any of them) cannot lead to an absolute conclusion about the antenna efficiency.



a) $F = 3.815$ GHz b) $F = 4.51$ GHz

Figure 3. Structure of current density lines on the antenna elements

At the same time, the dependences of return loss on frequency at fixed values of other parameters allow to judge about the presence of matching frequency bands, their width, and the value of return loss within these bands (which will indirectly indicate the efficiency of operation).

Among all antenna elements there are some that fulfil a dual role. On the one hand - they are important structural elements (for example, dielectric substrate, because on it are placed antenna elements), on the other hand - the parameters of the substrate affect both the spectrum of eigenwaves, and to a certain extent affect the input resistance of the antenna. The ratio of ε_r, h and the operating frequency determine the conditions of excitation of surface waves in the substrate. To improve the efficiency of the antenna seeks to operate in the regime of no surface waves. For operation in such a regime it is necessary to use so-called "thin" substrates. The conditions of such a mode will be determined by the relations of $h \ll \lambda_r$, $h \ll \lambda$, where λ_r is the resonant length of excited oscillations, λ is the operating wavelength. In the considered frequency range at the chosen value of $h = 0.5$ mm, such conditions are certainly fulfilled.

In Fig. 4 one can see the dependences of the magnitude $|S_{11}|$ on the substrate values ε_r at optimized values of the parameter $t = 2$ mm and the value of the gap between the coplanar line ring element and the ring resonator.

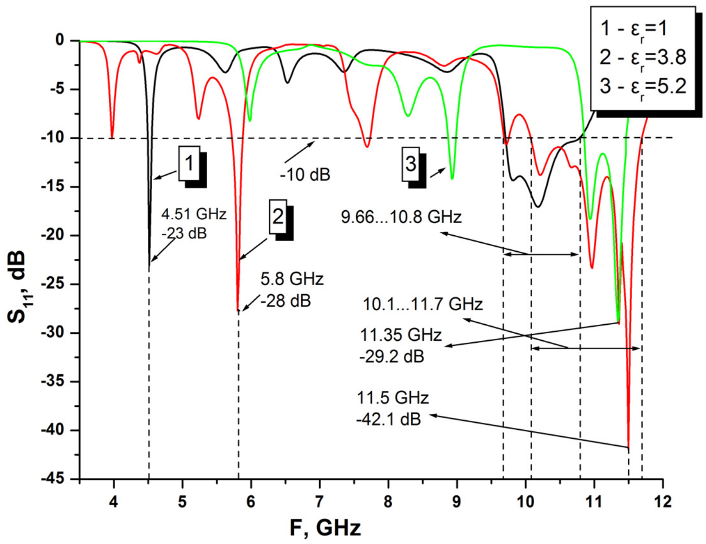


Figure 4. Dependencies of $|S_{11}|$ vs frequency with ε_r variation

All curves presented in the graph are oscillatory to a greater or lesser extent. Moreover, the local amplitudes of oscillations increase with increasing magnitude. There is a trivial effect of the shift of resonance frequencies to the lowfrequency region with decreasing value of ε_r. At all values of ε_r in the characteristics there are both narrow frequency bands with acceptable (and even very high) level of matching, and quite wide bands. Wide bands are observed in the high-frequency part of the considered frequency range.

It is typical that the minimum values of the $|S_{11}|$ are observed at frequencies coinciding or very close to the frequencies of spectral lines of eigentypes of oscillations in the structure (see Fig. 2). The maximum wide bandwidth, within which the matching at the level of -10 dB (VSWR=1.925) is observed, is provided at the value of $\varepsilon_r = 3.8$. It covers the range from 10.1 GHz to 11.7 GHz (approximately 14.7% of the sub-band center frequency). For this value of ε_r, the minimum value of the $|S_{11}| = -42.1$ dB at 11.5 GHz is also achieved. When the value of ε_r is reduced to unity, the bandwidth narrows and it is approximately 11.1% and when the value of ε_r is increased to 5.2 it is only 5.5%. From the results of the simulation we can conclude that the maximum matching levels are achievable only when the operating frequencies coincide with the frequencies of the spectral lines of the eigenoscillation types (or maximum close to them). However, the distribution of currents on the surface of the antenna elements shows (see Fig. 3) and the maximum matching levels do not guarantee effective excitation of apertures, hence, effective radiation.

The value of ε_r has a significant effect not only on the degree of matching but also on the antenna gain. Fig. 5 shows the dependence of the gain in dBi (according to IEEE classification) on frequency at variation of ε_r values.

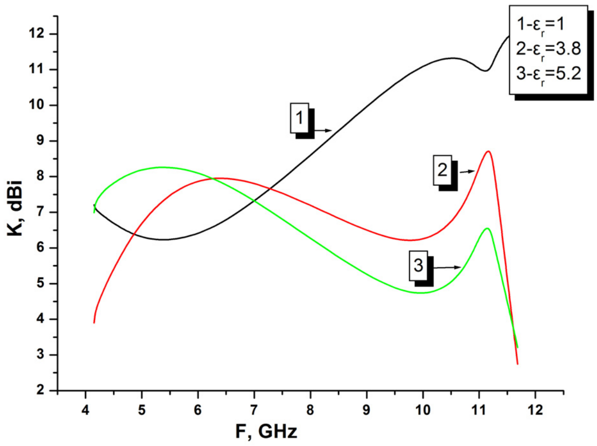


Figure 5. Dependences of the gain coefficient vs frequency at variation of the ε_r value

As it is evident from the above dependences, the frequency dependences have a fundamentally different character. If at value of $\varepsilon_r = 1$ the gain factor practically monotonically increases with frequency growth with two fluctuations of the value of the factor (within 9%), then with increasing ε_r value the dependences acquire oscillatory character (extrema are observed), and at the end of the frequency range there is a sharp decrease in the value of the gain factor. The maximum values of the gain also differ significantly. The maximum of 11.55 dBi is reached at $\varepsilon_r = 1$, at $\varepsilon_r = 3.8$ the maximum is 8.67 dBi, at $\varepsilon_r = 5.2$ the maximum is 6.52 dBi.

The most important characteristics of any antenna are energy and polarization characteristics. These characteristics determine the functionality of a particular antenna. Synthesizing antennas with given parameters has always been a difficult task, given the complex interrelated dependencies of the parameters. And, as indicated earlier, optimizing any of the antenna characteristics by a single parameter does not always lead to the desired result. This situation can be demonstrated by the example of the radiation pattern and ellipticity coefficient dependence of the antenna. Fig. 6 shows the pattern characteristics for some typical cases.

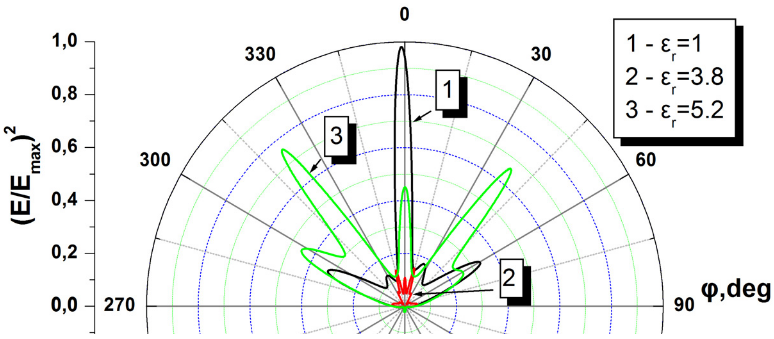


Figure 6. Pattern characteristics in azimuthal plane with optimized set of parameters

All diagrams are normalized to the global maximum (this allows us to compare the radiation efficiency at each frequency). The spline interpolation procedure was used to construct the dependencies and for this reason there is a visual difference from unity in the maximum of the directivity diagram. The lower part of the construction is excluded from consideration, because the value of the back lobes does not exceed the value of 0.015 (-18 dB).

The following frequencies were selected for analysis: curve 1 - at $F=4.51$ GHz ($|S_{11}|=-23$ dB), curve 2 - at $F=5.8$ GHz ($|S_{11}|=-28$ dB), curve 3 - at $F=11.35$ GHz ($|S_{11}|=-29.2$ dB). These frequencies were chosen from the consideration of minimum values of the return loss magnitude. The frequency with the absolute minimum ($|S_{11}|=-42.1$ dB at $F=11.5$ GHz) was not considered due to too large difference in the return loss values.

As it is obvious, at all fixed parameters and $\varepsilon_r=1$ quite sharp main lobe formed (its width at the level of 0.707 is 4.57^0), the side lobes are located symmetrically relative to the main one, their level does not exceed the value of 0.3. The main lobe is displaced from the normal by an angle of 1.9^0. Increasing the ε_r value up to the value 3.8 leads to radical changes in the directivity diagram. The level of radiated power decreases sharply (its value does not exceed 11% of the value of the level at $\varepsilon_r=1$). Further increase up to the ε_r value of 5.2 leads to increase of the radiated power up to the level of 73% of the maximum at $\varepsilon_r=1$. However, the diagram acquires a multi-lobe appearance.

Fig. 7 shows the polarization characteristics of the antenna plotted at the same parameter values and at the same frequencies. The characteristics are plotted in a limited range of observation angles. In the remaining of the range of angles, very sharp jumps in the value of the ellipticity coefficient are observed. As can be seen from the above characteristics, the dependence function of the ellipticity coefficient for the $\varepsilon_r=1$ value has a monotonically increasing character with a minimum value of 15 dB, which indicates the presence of linear polarization of the radiated waves. When increasing ε_r within the interval of angles 5.64^0, the η value does not exceed the value of 3 dB, which indicates the presence of elliptical polarization.

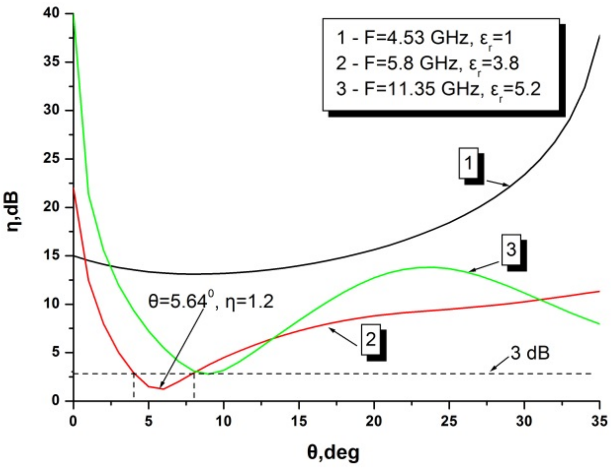


Figure 7. Polarization characteristics

At the $\varepsilon_r=5.2$ value of the dependence has an oscillatory character and in most of the values of the observation angles the polarization has a linear character. In a very narrow band of observation angles we can conditionally speak about the presence of elliptical polarization.

The analysis of the given energy and polarization characteristics confirmed the position that the process of optimization of multi-criteria characteristics of the antenna by one parameter is practically impossible. In order to achieve the desired parameter levels, a multi-criteria optimization procedure has to be carried out. Such a process is very complicated in terms of sufficiently large expenditures of calculation time and in terms of rather strict requirements to the capabilities of computing equipment.

CONCLUSION

This paper presents the results of numerical simulation of the main electrodynamic characteristics of a complex-composite electrodynamic structure designed to operate as an antenna in the centimeter wavelength range. The peculiarity of the method of excitation of the structure is actually two-port feeding of the antenna: the first port - due to the presence of galvanic coupling between the inner conductor of the excitation coplanar line and the ring conductor of the resonator, and the second - due to the distributed electromagnetic coupling of the outer conductor of the coplanar line and the ring resonator. By optimizing the varying parameters, it is possible to ensure satisfactory matching between the antenna and the external circuits. As a result of simulations it is established that this kind of design can provide effective radiation of electromagnetic waves with different types of polarization.

ORCID
Sergey A. Pogarsky, https://orcid.org/0000-0003-0833-1421; **Dmitry V. Mayboroda,** https://orcid.org/0000-0002-9564-2369

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АНТЕНА НА ОСНОВІ КОМПОЗИЦІЙНОЇ КОПЛАНАРНОЇ СТРУКТУРИ

Сергій О. Погарський, Дмитро В. Майборода, Сергій М. Михалюк
Харківський національний університет імені В.Н. Каразіна, майдан Свободи, 4, Харків, Україна, 61022

У цій роботі представлено результати чисельного дослідження площинної антени зі складним форм-фактором. Основу антени становить комбінація двох резонаторів - дискового та кільцевого. Збудження кільцевого резонатора здійснюється за допомогою копланарної структури: точково за рахунок гальванічного контакту центрального провідника копланарної лінії та кільцевого резонатора і за рахунок розподіленого електромагнітного зв'язку кільцевого резонатора й апертури зовнішнього провідника копланарної лінії. Антена розміщувалася над металевою площиною, геометричні розміри якої істотно перевищували геометрично розміри антени для виключення впливу крайових дифракційних ефектів. Під час чисельного моделювання використано комплексний підхід, що містить у собі метод напіввідкритого резонатора та метод скінченних елементів (МКЕ), реалізований у рамках комерційного пакета HFFS. Проведено дослідження залежностей спектральних, енергетичних і поляризаційних характеристик від матеріальних констант і частотного параметра. Встановлено, що в рамках однопараметричної оптимізації неможливе одночасне досягнення високого рівня всіх важливих параметрів. Значення частот спектральних ліній у спектральних характеристиках антени знайдено з відносною похибкою не гірше 1200 Гц. Встановлено частотні діапазони, у межах яких відсутнє виродження типів коливань. Наведено розподіли поверхневих струмів на металевих елементах антени, що дають змогу визначити положення фазових центрів збудження. Показано, що пропонована антена може забезпечувати прийнятний рівень узгодження як на окремих частотах, так і в доволі широких локальних смугах частот, що сягають 11% щодо центральної частоти піддіапазону. Встановлено граничні значення коефіцієнтів підсилення в частотних діапазонах. Результати моделювання дають змогу прогнозувати ефективне випромінювання з формуванням практично однопелюсткової діаграми спрямованості та наявність еліптичної поляризації.

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