АНТЕНИ, ХВИЛЕВОДИ І КВАЗІОПТИЧНА ТЕХНІКА

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THE INFLUENCE OF A CIRCULAR-PATCH MONOPOLE ANTENNAS EXCITATION METHOD ON THEIR INTEGRAL CHARACTERISTICS

Purpose: *The question of the influence of modes of excitation of disk monopole antennas of microstrip topology on the antenna general properties is considered. The purpose of work consists in determination of the optimum method of antenna excitation for increasing the antenna matching level with the external microwave chains and its influence on the antenna energy characteristics.*

Design/methodology/approach: *The modeling of antenna general properties is made by using the finite element method (FEM). The modeling is carried out within the model of a half-open resonator formed by the two metal surfaces (a grounded base and just a strip conductor), on which the condition of electric wall is fulfilled, and also by the cylindrical surface on which the condition of magnetic wall is fulfilled. In modeling, usually the thin substrate* $h \ll \lambda_{res}$ *is assumed, where h is a substrate thickness,* λ_{res} *being the resonance wave-length in a resonator. For such an assumption we may affirm that the vector of an electric field in a resonator will not have variations along the coordinate being perpendicular to the structure plane, and in the resonator, the prevailing types of oscillations will be oscillations* $E_{mn0}(TM_{mn0})$. *In modeling, special attention has been paid to the mutual coupling of just a disk resonator and the resonator formed by a coaxial line segment.*

Findings: *The information on the influence of the mode of excitation of disk monopole antenna with microstrip topology on the antenna general properties: spectral characteristics, degree of antenna matching with external chains, and energy characteristics with variation of substrate dielectric constant values is obtained.*

Conclusions: *The data obtained testify that the monopole disk microstrip resonators with the complex-composite topology of radiators can provide a high level of integral characteristics and form the radiated fields with the required characteristics.*

Key words: *disk microstrip resonator, slot radiator, mode of excitation, matching, directivity diagram*

1. Introduction

This paper is an extension of work originally presented in 2017 at the XI International Conference on Antenna Theory and Techniques (ICATT) [1] and describes new results in the field of microwave and wireless technologies.

Microstrip antennas, due to their lightweight, compact size, conformable structure and ease of fabrication, have found wide application in various fields. They are widely used in many communication systems as independent transmitting or receiving antennas, and as elements of phased array antennas. In particular, microstrip antenna is used as a receiving antenna in user's apparatus of space navigation systems (GPS (Global Positioning System), GLONASS (Global Navigation Satellite System), etc.) [2], in modern wireless communication systems [3], etc. Other fields of applications should be mentioned such as medical therapy [4], elements of microstrip devices (filters [5], hybrid junctions [6], circulators [7], etc.).

Recently, applications in military radio technology have become an important subject of microwave communication [8]. For these applications, a set of different (and sometimes contradictory) requirements is presented. They have to be compact, extremely wideband and to provide the ability to receive and transmit signals accounting for the possible rapid movement of the object and thus possible frequency changes due to the Doppler effect.

The canonical forms of microstrip antennas are rectangular and circular resonators and their various modifications operating at the lowest modes. Each of topology realization has its own advantages and disadvantages. For example, a rectangular patch design topology has resonant wavelengths proportional to $1/\sqrt{\varepsilon_r}$ (ε_r means relative permittivity of a substrate material). It allows to use substrates with large values of permittivity and thus to reduce the geometrical antenna dimensions at required frequencies.

Antennas with axially symmetric type topology (circular, annular, and their modifications) have certain advantages as against antennas with a rectangular topology. A wide operating frequency band and the possibility of radiation with an elliptical (circular) polarization are the two most significant. At the same time, the designs based on these topologies have a significant defect. In these structures, the degenerated modes may be excited that can be result in technical difficulties in maintaining a single-mode operation and polarization stability in a given frequency band. In axially symmetrical resonating structures, multiple degenerated eigenmodes are observed because of the presence of infinite symmetry around the rotation center (axis of symmetry equals C_∞) [9]. The information on sufficiently simple and technological ways of controlling the spectral composition of the excited oscillations can be found. Among them, one can point to the methods based on changing the structure of the current lines on the patch surface [10], and to methods based of the effect on the so-called phase excitation centers [11, 12].

Analysis of information cited in studies that have already became classical [13–15] shows that the problems of excitation of microstrip structures and matching them with external circuits have received much attention. The aforementioned studies focused mostly on matching by the use of 3D elements (shorting vias). These studies lack data on spectral interactions between two primary parts of a structure, namely a resonator and an exciting element. Due to finiteness of geometrical dimensions of exciting elements and the possibility of appearance of resonances in these elements, the spectral interactions factor can't be ignored in the process of designing highly efficient antenna systems.

There were attempts to create models for simulations of an input impedance value, matching and frequency tuning of microstrip antennas [16–20]. They also have not accounted for the factor of possible occurrence of resonance effects and its influence on integral characteristics of antennas. Reviewed literature also lacks information on the influence of relatively small deviations of values of a dielectric permittivity on amplitude-frequency and other characteristics of antennas with various technological methods of antennas excitation.

Obviously, a detailed analysis of the influence of various technological factors on the most important antenna characteristics is very important.

In this regard, an attempt was made to fill such gaps. The goal of this study was to identify more subtle mechanisms of the influence of various technological factors on the most important characteristics of circular-patch monopole antennas.

2. Models under Study

Now let us study a microstrip disk patch antenna with discontinuities in the form of log-periodic slot line segments being excited by different methods shown in Fig. 1(*a*)–1(*c*). Elements of discontinuities fulfil conditions of the log-periodic law, that is, the distance between the elements and the size of the cell changes are decreasing up to geometric progression with a given denominator. In Fig. 1(*a*), the patch antenna is excited with a coaxial line segment. In Fig. 1(*a*), the following notations are used: 1 – grounded plane, 2 – dielectric substrate, 3 – disk patch, 4 – exciting segment of a coaxial line.

In Fig. 1(*b*) the structure is excited with a microstrip line segment. In addition, Fig. 1(*c*) shows the structure excited with a coplanar line. Each excitation method has certain electrodynamic and technical advantages. Thus, excitation with a coaxial line allows to excite the axially symmetric types of oscillation quite easily.

Excitation with a microstrip and coplanar lines makes it possible to match the antenna with external circuits without any technical tricks. Furthermore, the excitation with a coplanar line allows to achieve the radiation from both sides of the substrate (to achieve the radiation from both sides of the aperture).

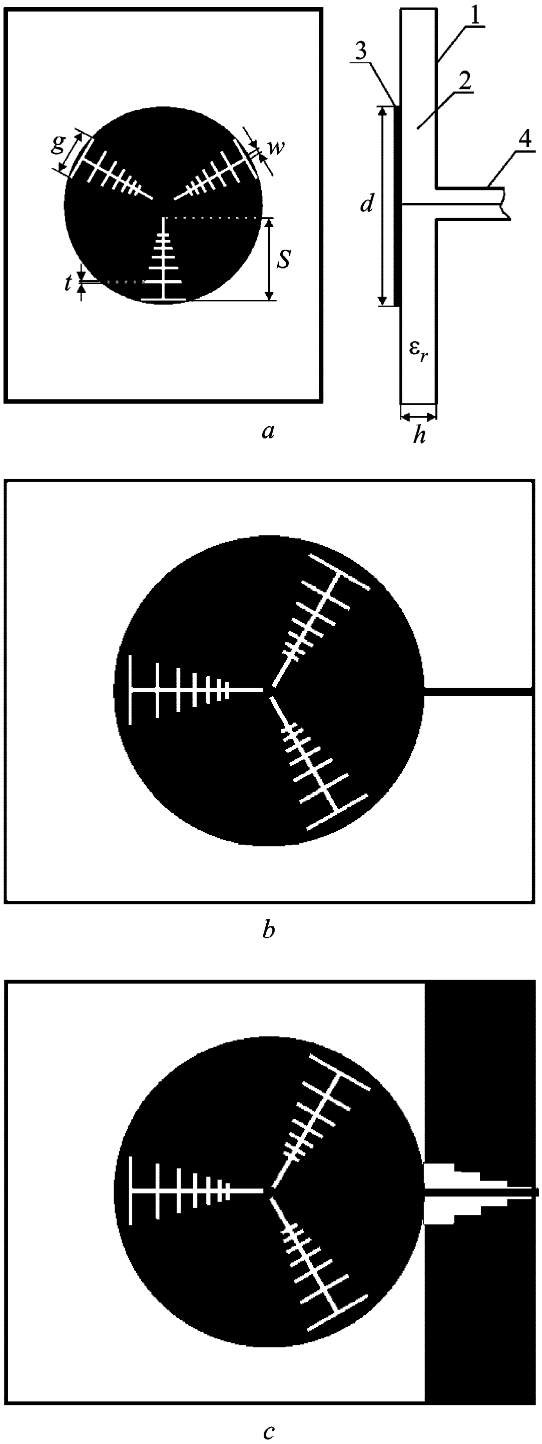

Fig. 1: A structure with coaxial excitation shown schematically (a), topology of the structure with microstrip excitation (b), and topology of the structure with coplanar excitation (c)

The used parameters of a structure under study are as follows: dielectric substrate is FLAN-3.8 ($\varepsilon_r = 3.8$) with thickness of $h = 0.5$ mm, disk patch with diameter of $d = 35$ mm, the angle between neighbouring segments is 120° (between axes of channels of a log-periodic structure). In the first case, the exciting segment of a coaxial line has the cross section of 7.5×3.8 mm and wave resistance 50 Ω. In other cases, the parameters of exciting elements have been taken with account for matching with external circuits. It will be observed that in the case of coplanar excitation, there is a too large difference between the values of the wave resistance of the coplanar line and the input resistance of the patch, the coplanar transition is made in a stepwise form. In all cases, the values of dielectric constant are variable.

As can be seen from the ratio of the parameters, the substrate has been assumed to be thin $(h \ll \lambda_r)$, wherein h is the substrate thickness, λ_r is the resonant wavelength in the cavity. If such assumptions are made, it can be argued that the vector of an electric field in the resonator has no variations along the direction perpendicular to the structure plane and the cavity oscillation modes $E_{mn0}(TM_{mn0})$ are prevalent oscillations.

3. Results of Investigation

The key issues in the study of any microstrip structure with canonical topology of the patch are eigenmode spectrum, influence of internal parameters on integral characteristics, broadbandness of operation, and – if it is a radiating structure – the form and characteristics of patterns. By the FEM (Finite Element Method), the eigenmode spectra of a complicated structure for different methods of excitation are investigated.

Fig. 2 shows the spectrum of a canonical disk resonator. The concentration of spectral lines can be observed in the frequency range above 5 GHz. In the frequency range above 6 GHz, there is a large number of degenerated modes (in Fig. 2 they are shown with the thickened spectral lines).

Fig. 3 shows the spectrum of object with three discontinuities in the form of segments of log-periodic structure with a coaxial segment. It will be observed that in any case a disk patch with discontinuities and an element of excitation will together make a system of coupled resonators. The relationship between the resonant frequencies and the coupling magnitude will determine the actual spectral characteristics. In the case of excitation with a coaxial segment, the rarefying of eigenmodes spectrum can

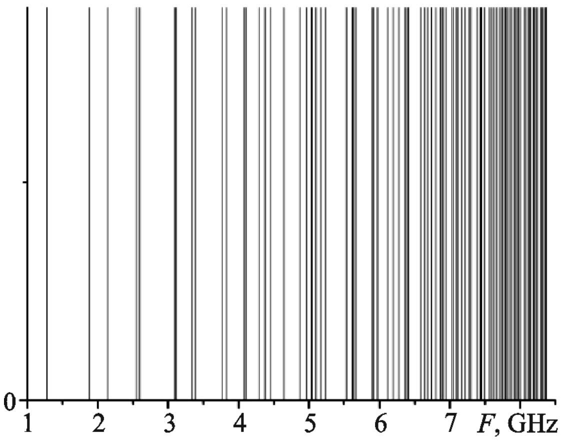

Fig. 2: Spectrum of a canonical microstrip disk resonator

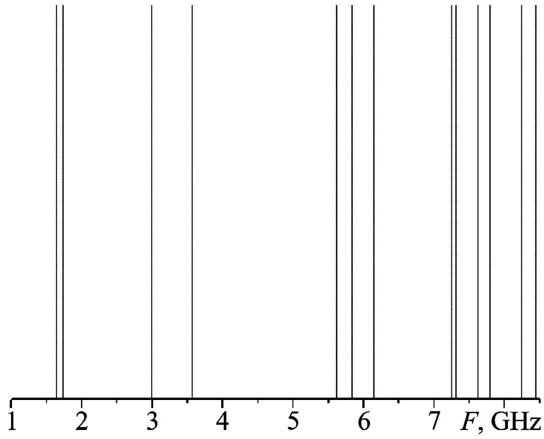

Fig. 4: Spectrum of the structure with three discontinuities and a segment of microstrip line

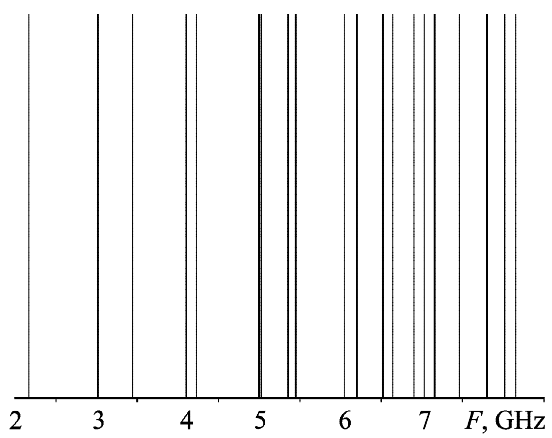

Fig. 3: Spectrum of the structure with three discontinuities and a segment of coaxial line

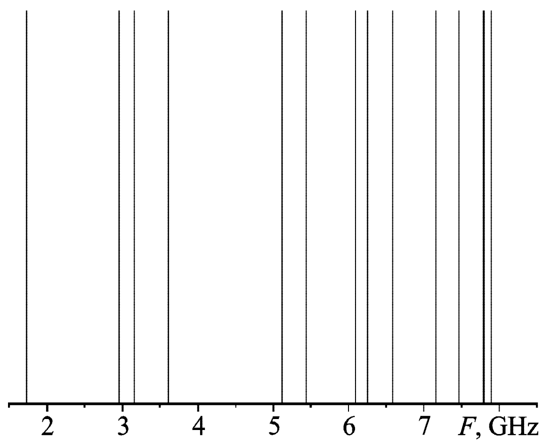

Fig. 5: Spectrum of the structure with three discontinuities and a segment of coplanar line

be noted. Only two spectral lines at frequencies $F = 5.0003$ GHz and $F = 5.0333$ GHz are sufficiently close but not degenerated. This fact is confirmed by the current structure on the patch obtained by numerical simulations.

Fig. 4 shows the spectrum of an object excited by a segment of microstrip line.

Here, a sufficiently rarefied spectrum in the entire frequency band can be found. Only two spectral lines at frequencies $F = 6.144$ GHz and $F = 8.012$ GHz are degenerated.

Fig. 5 shows the spectrum characteristic of a structure with coplanar element of excitation. A sufficiently large number of spectral lines can be seen. They are distributed rather unevenly on the frequency axis. Degenerated modes are observed in the frequency band above 7 GHz.

It is a well known fact that all parameters of microstrip devices depend essentially on the internal parameters, first of all, on the permittivity value of a dielectric substrate. This parameter is of particular importance in cases where discontinuities which change the structure of currents on the patch are present. In addition, an important role is played by the method of excitation of the structure, more precisely, by the presence of additional functional elements. The permittivity value on influence $|S_{11}|$ in the frequency range will determine both degree of antenna matching with external circuits and radiation efficiency at certain frequencies. Dependencies of $|S_{11}|$ vs. frequency with variation of the relative permittivity values in case of a coaxial excitation (Fig. 1(a)) are shown in Fig. 6.

As can be seen, the minimum of $|S_{11}|$ is observed for $\varepsilon_r = 3.7$ at $F = 5.75$ GHz with an absolute value

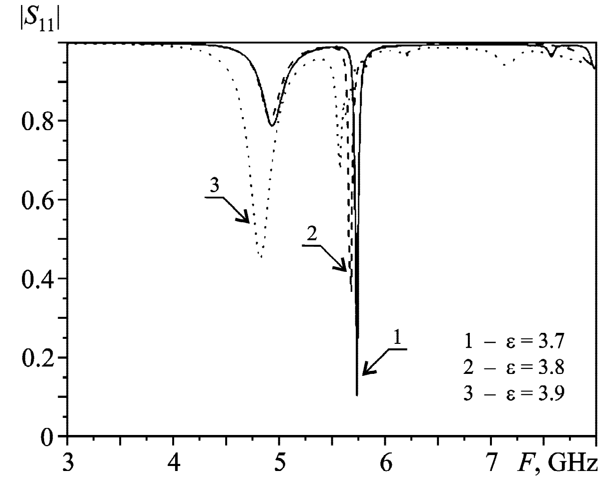

Fig. 6: Dependencies of $|S_{11}|$ vs. frequency with variation of the ε_r value for a coaxial excitation case

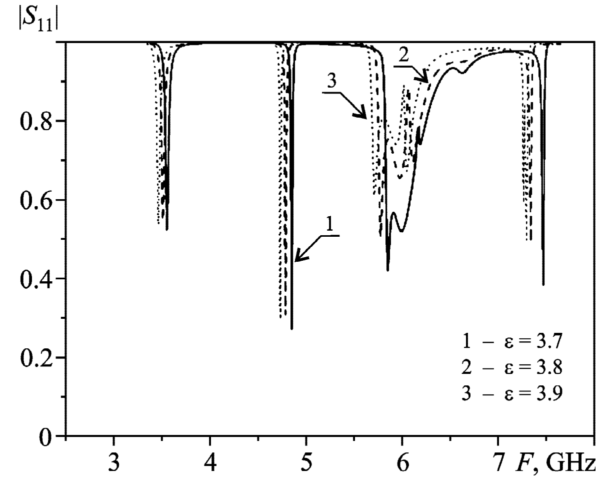

Fig. 7: Dependencies of $|S_{11}|$ vs. frequency with variation of the ε_r value for a microstrip excitation case

of 0.11 that is equivalent to voltage standing wave ratio $VSWR = 1.247$. This frequency corresponds to the frequency of one of the degenerated modes of a canonical microstrip disk resonator (Fig. 2). It will be observed that this absolute minimum can be seen in a very narrow frequency band. A small change in the relative dielectric constant to the design value of $\varepsilon_r = 3.8$ (about 2.6 %) shifts the minimum value of $|S_{11}|$ to a low frequency region. The resonant frequency is almost equal to the frequency of the spectral line of one of the eigenmodes of a disk with log-periodic discontinuities (Fig. 3). The bandwidth in this case practically does not change, but the value of $|S_{11}|$ itself rises to the level of 0.36 (equivalent to the value of $VSWR = 2.125$). Further increasing of the relative dielectric permittivity value to $\varepsilon_r = 3.9$ leads to a further shift into a low frequency band and increases the $|S_{11}|$ level. We may assume that at frequencies close to the minima of the reflection coefficient, an effective radiation can be detected.

However, in the low frequency band (near $4.75 - 4.85$ GHz), where the $E_{410}(TM_{410})$ mode is excited, there are resonances with a relatively low level of reflection (not exceeding the level of 0.45). Resonances at these frequencies are not so sharp, that is, the bandwidth here is wider.

Fig. 7 shows the changes of $|S_{11}|$ with variations of the ε_r value within 3.7 to 3.9 for the case of a structure excitation using the segment of microstrip line (Fig. 1(*b*)). As can be seen, there are some changes with respect to the first case (Fig. 6). All the dependences show a shift to the low-frequency region by about 1 GHz. There is also a small frequency shift down the frequency with increasing value of ε_r. The magnitude of the absolute minimum of $|S_{11}|$ has slightly increased. At the same time, there are two more frequency bands in the considered frequency domain, within which small values of $|S_{11}|$ are observed.

Typical is the frequency band from 5.5 to 6.5 GHz. In this band, sufficiently strong oscillations of $|S_{11}|$ values are observed, that is the result of resonant phenomena in a microstrip line segment. The segment length is $l \approx 12.5$ mm, the average frequency of the interval is 6 GHz, the obtained value of $\varepsilon_{eff} \simeq 1.688$, the ratio is $l/\lambda \approx 0.42$, i.e. the situation is close to the resonant one.

Fig. 8 shows the changes of $|S_{11}|$ vs. frequency with variations of the ε_r value for coplanar excitation case. The dependencies have substantial differences from the earlier considered cases. Obviously, there is no principle dependence of $|S_{11}|$ vs. ε_r in the frequency band from 1 to 14 GHz. The noticeable pulsations are observed in the high-frequency band. The resonant phenomena associated with the finiteness of the segment of an exciting element are observed in a higher frequency range. Taking into account the nature of the characteristic, one can expect the effective radiation of a structure in two bands, one of which being a sufficiently low-frequency.

The results of numerical simulations of energy characteristics are shown in Fig. 9. Fig. 9 shows the elevation pattern characteristic for $F = 4.78$ GHz and $F = 5.74$ GHz being normal with respect to the plane of the disk resonator structure. Characteristics

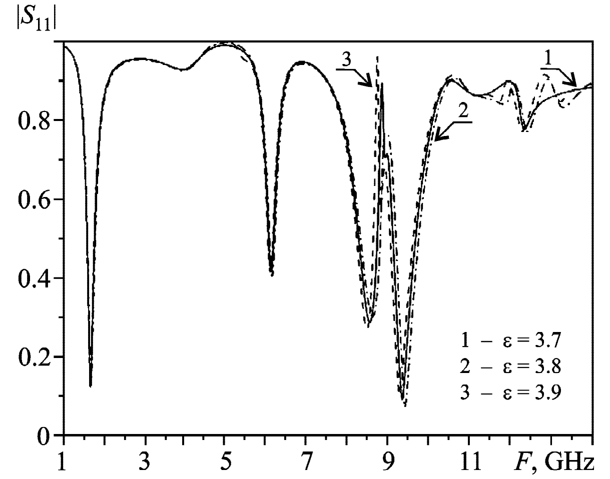

Fig. 8: Dependencies of $|S_{11}|$ vs. frequency with variation of the ε_r value for a coplanar excitation case

are double-lobe, because microstrip patch is excited by a non-axially symmetric mode. Both characteristics are represented in absolute values. This representation gives an indication of the radiation efficiency. As expected, more effective radiation was found at the frequency for which minimum reflectance is observed. Comparison of both characteristics shows that at $F = 5.74$ GHz the radiated power is much more effective. In addition, at this frequency the angular dimensions of lobes with an effective radiation are substantially wider.

Fig. 10 shows the pattern characteristics of a structure with microstrip excitation for $F = 4.86$ GHz. This frequency corresponds to the minimum value of $|S_{11}|$ (see Fig. 7).

Curve 10a shows the elevation characteristic (with the azimuth angle of 0°) and curve 10b shows the azimuthal dependence. Both characteristics are single-lobe. The elevation dependence had small oscillations of radiated power. The fluctuations are observed at angles, which determine the position of the longitudinal axes of segments of the meander line on the patch surface. The difference in the radiated power varies insignificantly.

Fig. 11 shows the pattern characteristics of a structure with coplanar excitation for $F = 1.66$ GHz.

Curve 11a corresponds to the elevation characteristic (with the azimuth angle of 90°) and curve 11b shows the azimuthal dependence. Both characteristics are double-lobe. It will be observed that the radiation level from the side of a substrate free of metallization is somewhat larger. In addition, the angular width with the maximum of a radiation also turns out to be wider. Both observed facts are explained by the influence of a dielectric substrate, which ensures the redistribution of the electromagnetic field to the side of aperture with a large value of permittivity.

4. Conclusions

Thus, the studies of complicated structures being microstrip objects with complex configuration of discontinuities, show that in order to design the effective radiating systems, it is necessary to take into account a number of important factors. The first one is the influence of material characteristics of the substrate on radiation characteristics. Accounting for the fact that there are no perfect dielectrics, they always have different kinds of defects, including deviation from the desired ε_r, it is an important factor in designing the radiators, which can be well matched to external cir-

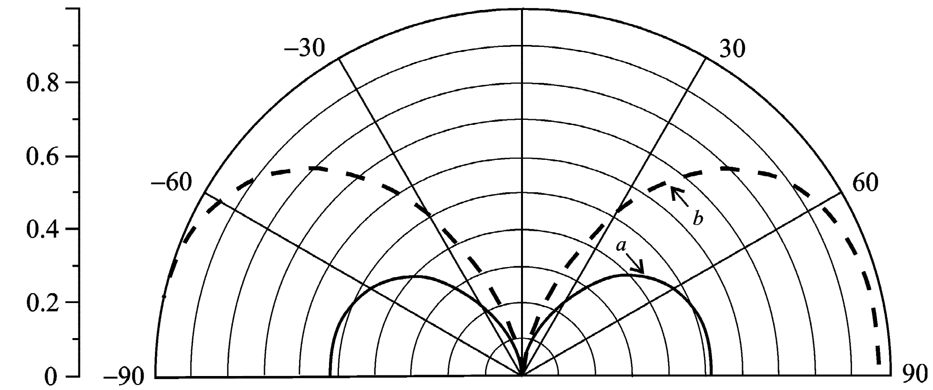

Fig. 9: Elevation pattern characteristic for a coaxial excitation case: curve *a* – $F = 4.78$ GHz, curve *b* – $F = 5.74$ GHz

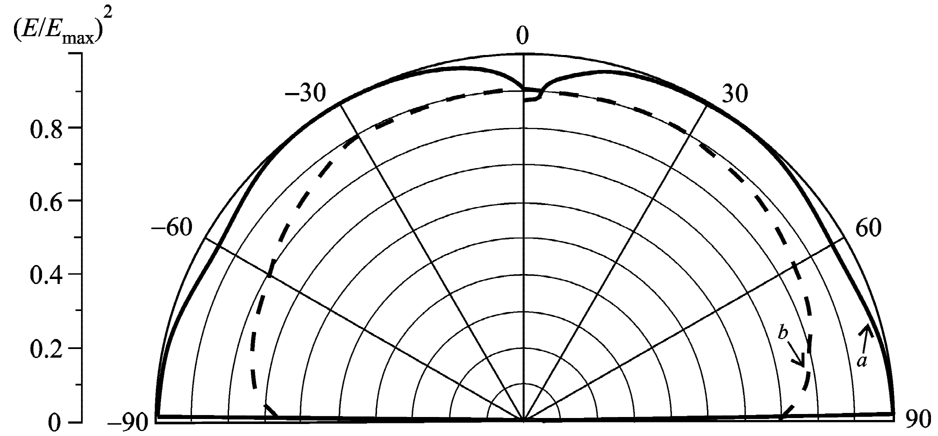

Fig. 10: Pattern characteristic for a microstrip excitation case

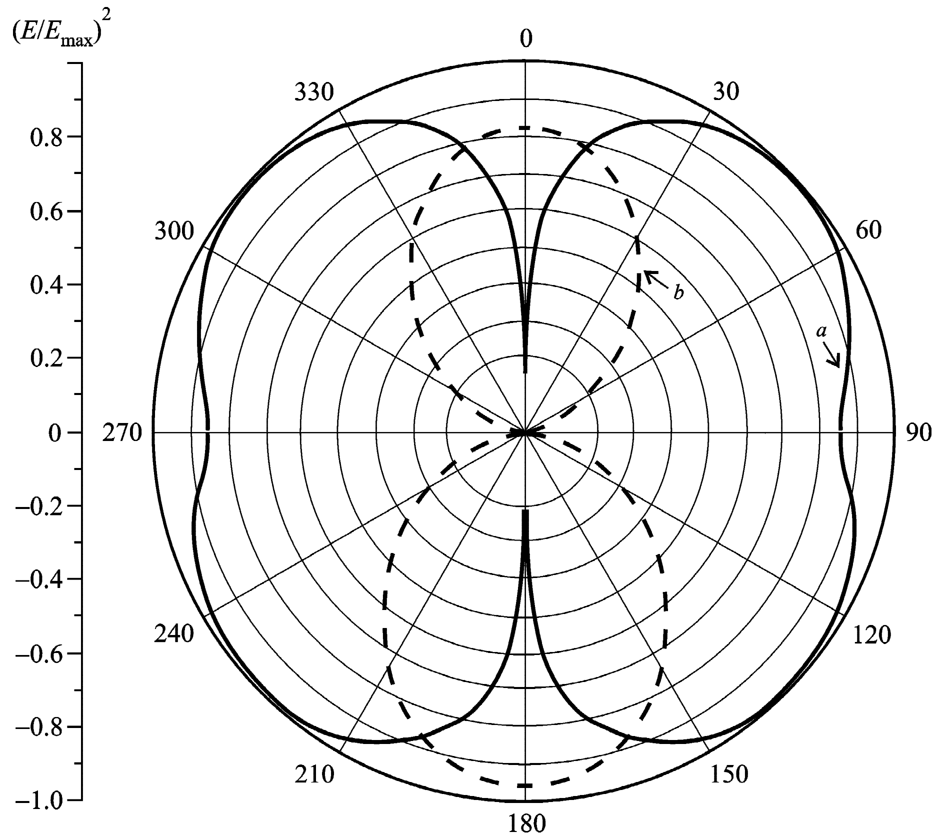

Fig. 11: Pattern characteristic for a coplanar excitation case

cuits at one or several frequencies or in a certain frequency band. The second one is the influence of excitation method on spectral and radiation characteristics. The influence on both characteristics is explained by the fact that a circular-patch monopole (with discontinuities) and a segment of an exciting line represent two independent resonating systems. Besides, in exciting elements may be observed resonance effects associated with finiteness of their dimensions. The ratio of the resonant frequencies has a significant effect on the spectral characteristics. Moreover, the ratio of Q-factors has a significant effect on the radiation characteristics too. Consideration of the influence of these factors makes it possible to design the effective radiating systems with predictable characteristics. Use of excitation with a segment of coplanar line allows to achieve effective radiation in the low frequency range. Use of other methods of excitation fails to realize effective radiation in this frequency range with the same geometric dimensions of the structure.

The results of investigations have allowed to design a sample of the antenna being patented in Ukraine [21].

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ВЛИЯНИЕ СПОСОБОВ ВОЗБУЖДЕНИЯ ДИСКОВЫХ МОНОПОЛЬНЫХ АНТЕНН НА ИХ ОСНОВНЫЕ ХАРАКТЕРИСТИКИ

Предмет и цель работы: Рассматривается вопрос о влиянии способов возбуждения дисковой монопольной антенны микрополосковой топологии на основные характеристики антенны. Цель работы состоит в определении оптимального способа возбуждения антенны для повышения уровня согласования антенны с внешними СВЧ цепями и его влияния на энергетические характеристики антенны.

Методы и методология: Моделирование основных характеристик антенны осуществлено с использованием метода конечных элементов (FEM). Моделирование проведено в рамках модели полуоткрытого резонатора, образованного двумя металлическими поверхностями (заземленное основание и собственно полосковый проводник), на которых выполняется условие электрической стенки, и цилиндрической поверхностью, на которой выполняется условие магнитной стенки. При моделировании обычно вводят предположение тонкой подложки $h \ll \lambda_{res}$, где h – толщина подложки, λ_{res} – резонансная длина волны в резонаторе. При такого рода предположении можно утверждать, что вектор элект-

рического поля в резонаторе не будет иметь вариаций вдоль координаты, перпендикулярной плоскости структуры, а в резонаторе превалирующими типами колебаний будут колебания $E_{mn0}(TM_{mn0})$. При моделировании особое внимание уделено взаимному влиянию собственно дискового резонатора и резонатора, образованного отрезком коаксиальной линии.

Результаты: Получены данные о влиянии способа возбуждения дисковой монопольной антенны с микрополосковой топологией на основные характеристики антенны: спектральные характеристики, степень согласования антенны с внешними цепями и энергетические характеристики при вариации значений относительной диэлектрической проницаемости подложки.

Заключение: Полученные данные свидетельствуют о том, что монопольные дисковые микрополосковые резонаторы со сложнокомпозиционной топологией излучателей могут обеспечивать высокий уровень интегральных характеристик и формировать излучаемые поля с требуемыми характеристиками.

Ключевые слова: дисковый микрополосковый резонатор, щелевой излучатель, способ возбуждения, согласование, диаграмма направленности

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ВПЛИВ СПОСОБІВ ЗБУДЖЕННЯ ДИСКОВИХ МОНОПОЛЬНИХ АНТЕН НА ЇХ ОСНОВНІ ХАРАКТЕРИСТИКИ

Предмет і мета роботи: Розглядається питання про вплив способів збудження дискової монопольної антени мікросмужкової топології на основні характеристики антени. Мета роботи полягає у визначенні оптимального способу збудження антени для підвищення рівня узгодження антени із зовнішніми НВЧ ланцюгами і його впливу на енергетичні характеристики антени.

Методи і методологія: Моделювання основних характеристик антени здійснене з використанням методу кінцевих елементів (FEM). Моделювання виконано в рамках моделі напіввідкритого резонатора, утвореного двома металевими поверхнями (заземлена основа та власне смужковий провідник), на яких виконується умова електричної стінки, та циліндричною поверхнею, на якій виконується умова магнітної стінки. При моделюванні зазвичай вводять припущення тонкої підкладки $h \ll \lambda_{res}$, де h – товщина підкладки, λ_{res} – резонансна довжина хвилі в резонаторі. За таким припущенням можна стверджувати, що вектор електричного поля в резонаторі не матиме варіацій уздовж координати, перпендикулярної площині структури, а в резонаторі переважаючими типами коливань будуть коливання $E_{mn0}(TM_{mn0})$. При моделюванні особливої уваги приділено взаємному впливу власне дискового резонатора і резонатора, утвореного відрізком коаксіальної лінії.

Результати: Отримано дані про вплив способу збудження дискової монопольної антени з мікросмужковою топологією на основні характеристики антени: спектральні характеристики, міра узгодження антени із зовнішніми ланцюгами і енергетичні характеристики при варіації значень відносної діелектричної проникності підкладки.

Висновок: Отримані дані свідчать про те, що монопольні дискові мікросмужкові резонатори із складнокомпозиційною топологією випромінювачів можуть забезпечувати високий рівень інтегральних характеристик і формувати випромінювані поля з необхідними характеристиками.

Ключові слова: дисковий мікросмужковий резонатор, щілинний випромінювач, спосіб збудження, узгодження, діаграма спрямованості

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