V.N. Karazin KHARKIV NATIONAL UNIVERSITY

Valery V. Radchenko

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RADIATION OF ELECTROMAGNETIC WAVES BY SPHERICAL CONFORMAL PRINTED ANTENNAS

01.04.03 – RADIO PHYSICS

SUMMARY
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Academic Supervisor: **Professor Alexander I. Nosich, D.Sc.**
O.Y. Usikov Institute of Radio-Physics and Electronics of the National Academy of Sciences of Ukraine, Kharkiv
Leading Scientist of the Department of Computational Electromagnetics

Official Reviewers: **Professor Nikolay N. Kolchigin, D.Sc.**
V.N. Karazin Kharkiv National University, Kharkiv
Head of Department of Theoretical Radiophysics

Senior Scientist Dozyslav B. Kuryliak, D.Sc.
G.V. Karpenko Institute of Physics and Mechanics of the National Academy of Sciences of Ukraine, Lviv
Leading Scientist of the Department of Electromagnetic Foundations of Nondestructive Sensing and Diagnostics

Reviewing Organization: Kharkiv National University of Radio Electronics, Kharkiv
Department of Radio Engineering and Department of Mathematics

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Secretary of the Specialized Scientific Jury A.F. Lyakhovsky, Ph.D.

GENERAL DESCRIPTION

Timeliness of research. This Ph.D. project is dedicated to the investigation of microstrip antennas (MSAs), which have the shape of the perfectly electrically conducting (PEC) spherical disk and are placed on the spherical "ground" with a dielectric substrate. The interest in these antennas is caused by the wide use of MSAs in the systems of cellular, mobile, aerospace communication and radar. These antennas favorably respond to the current demands of RF and microwave equipment miniaturization, its enhanced efficiency, and convenience of use[1]. Besides, implementation of MSAs enables one to develop the systems satisfying very strict and contradictory demands to their electrical and aerodynamic characteristics and also allows reducing their weight and cost. This especially regards to the space-borne antennas and feeding circuits: for instance, as a spaceship antenna systems may occupy about 20% of its total surface, small-thickness conformal MSAs are very attractive for such applications. They have the necessary mechanical and temperature characteristics, are able to radiate electromagnetic waves with linear, circular and elliptic polarization, and can operate in dual-frequency and multi-frequency regimes. These antennas can be easily combined into phased arrays and placed on the complicated-shape surfaces.

Furthermore, due to the rapid development and spread of mobile telephone communication systems, both customers and producers feel concern about the influence of these systems on the human tissues and organs, especially in the case of long-term use. Today, common standard of permissible Specific Absorption Rate (SAR) is 4 W/kg. It determines the absorbed power threshold, after which microwave radiation notably affects the organism. Even though the power generated of a high-frequency mobile telephone device is small (about 600 mW in free space), many researchers try to estimate the part of this power absorbed in the user body. In the first place, this relates to a telephone antenna placed close to the human head. It has been already shown that even a simplified spherically-layered model of the human head allows estimating correctly the absorbed power value[2]. It is also clear that absorption can be reduced by a protective helmet carrying a dipole antenna on its outer surface. However there is no published example of estimation how this reduction depends on the parameters of the helmet.

A study of all mentioned problems demands elaboration of the efficient models and computational algorithms able to simulate electromagnetic fields radiated by the conformal MSAs on the spherical surfaces, or by the dipole antenna in the presence of an absorbing body with a conformal screen. Here, many approximate methods have been proposed that can be divided into two broad categories: simplified physical ones and direct numerical ones. To the first category, a well known cavity method belongs, which is suitable for modeling of both planar and conformal MSAs on very thin substrates. As for the second category, the finite difference method must be mentioned, especially in the time domain (FDTD). This method approximates differential operators by finite differences. The difficulties in this method application relate to the necessity to invert matrices of large dimensions to reach practically acceptable accuracy. Therefore it requires considerable computer-time and memory resources even if a supercomputer with parallel processors is available. Another known numerical method, with a greater involvement of analytical derivations, is the Method of the Moments (MM), which is based on the discretization of the accurate integral equations (IE) for equivalent currents. The electromagnetic boundary-value problems for thin conductors often generate singular IEs of the first kind, which have no guaranteed convergence of MM-type solution algorithm, and sometimes this convergence does not exist at all. Although less computationally expensive than FDTD, the MM also requires considerable computing time and loses its accuracy in the vicinity of resonances. Usually the sphere of these methods use is restricted to the problems of analyzing the objects of small electrical dimensions. Therefore the analysis of conformal MSAs (especially

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[1] K.-L. Wong, *Design of Conformal Microstrip Antennas and Transmission Lines*, New York, Wiley, 1999.

[2] H.-Y. Chen, H.-P. Yang, SAR affected by shapes and electrical properties of the human head exposed to a cellular phone, *Microwave and Optical Technology Letters*, 2004, vol. 42, no 1, pp. 1-4.

spherical ones) with the aid of more efficient and reliable numerical methods is a timely and important research problem.

Relation to R&D projects and programs. The research has been performed in the context of R&D activity of the Department of Computational Electromagnetics of IRE NASU, as a part of the NASU projects # 01.94U031134, “Mathematical models, databases and integral media in electromagnetics of millimeter wave range” and # 0100U006441, “Theoretical and experimental investigation of wave processes in the devices and systems of microwave and millimeter wave ranges”. The thesis is connected also with the project “Modeling of conformal disk microstrip antennas printed on spherical dielectric substrates” of the Institute of Electronics and Telecommunications of Rennes (IETR) of the University of Rennes 1, Rennes, France.

The object of research is electromagnetic field in the presence of the metallic and dielectric scattering and absorbing bodies shaped as layered spheres and spherical disks. Namely, we study electromagnetic wave radiation by the conformal spherical MSAs, resonance phenomena, which take place inside and around such structures, and absorption of the electromagnetic field of a dipole antenna in a lossy dielectric sphere.

Therefore the following electromagnetic-field problems are considered in this thesis:
a) radiation of waves by a printed spherical-circular disk antenna excited in the axially symmetrical way by an elementary radial electric dipole as a model of coaxial probe,
b) radiation of waves by a printed spherical-circular disk antenna excited by an elementary tangential magnetic dipole, as a model of a slot in the ground conductor, located on the symmetry axis of the antenna,
c) electromagnetic wave absorption in the double-layer partially screened lossy dielectric sphere excited by a radial electric dipole located above the external screen surface on its axis of rotational symmetry.

The primary aims of our research are: (a) reduction of the mentioned electromagnetic boundary-value problems characterizing radiation of the electromagnetic wave by antennas to the sets of algebraic equations having stable solution, (b) development and the testing of the effective numerical solution algorithms for these equations, (c) the computation of the radiation fields of the spherical conformal MSAs and the physical analysis of the dependences of their characteristics on the problem parameters, and also (d) the evaluation of the electromagnetic power, which is absorbed in a partially screened lossy sphere.

Method of research. To analyze the radiation of waves by spherical conformal MSAs and other similar problems, we use the method of analytical regularization (MAR). This analytical-numerical method is based on the accurate statement of the problem that includes Maxwell equations, boundary conditions, radiation conditions, and condition of the power finiteness in arbitrary finite volume. Each boundary-value problem is reduced to a set of the dual series equations (DSEs) due to the rotational symmetry of considered models. Each of these sets allows explicit inversion of its static or asymptotically main part for a solitary spherical disk in free space. As a result an infinite-order matrix equation of the second kind is obtained. This provides guaranteed convergence and controlled accuracy of the numerical solution in any finite range of the frequency and other parameters variation, including the cases of resonance phenomena. The algorithms based on MAR do not demand large the computer time and memory expenditures. One may use them for calculation of the surface currents in the conductors and radiation fields of the MSAs and also for computation of absorbed power and other characteristics. They allow varying, in the very wide range, the geometrical and material parameters of the problems and the frequency, which may change from quasi-statics to quasi-optics.

The novelty of research is determined by the following original results obtained:

- For the first time a systematic investigation of the spherical conformal MSAs has been performed in the accurate statement by using the MAR, which provides guaranteed convergence of numerical algorithms,
- It has been found that the radiation resistance or conductance of the spherical conformal MSA has a resonant behavior, which is connected to the cavity resonances (which are the most interesting ones), high-frequency resonances on the quasi-surface waves on the dielectric substrate, and also a low-frequency resonance of the metallic sphere,
- It has been shown that, if the frequency grows, a “keel over” of the radiation pattern (RP) main beam takes place, i.e. it starts radiating mainly in the direction opposite to the disk. This keel over is not observed in the models of MSAs, which have infinite PEC ground plane. This phenomenon is explained by the quasi-surface waves of spherical substrate that reach the shadow side of MSA and interfere with each other,
- It has been shown that a half-spherical PEC screen reduces in approximately 100 times the level of the electromagnetic wave absorption in a double-layer dielectric sphere with electrophysical parameters of a human head.

The practical importance of the obtained results is associated with the fact that they can be used both in design and in practical applications of the real conformal MSAs, which are important elements of the mobile, aerospace, and wearable communication systems. We have established a number of interesting features of the electromagnetic field radiated by these antennas. This considerably deepens the understanding of phenomena that accompany the antenna operation. Thus the obtained results show the ways of the elaboration of more complicated printed antennas with the improved characteristics. Besides, the used earlier analysis methods did not allow computing the antenna characteristics with guaranteed accuracy and thus could not serve as a basis for numerical optimization of these antennas – unlike our solutions.

Author’s personal contribution is proven by a number of the journal and conference papers, which have been published in 1998- 2006. In the published with the co-authors works [1,2,6-8,10,13] the author used the theoretical approach on the basis of MAR for analyzing the considered electromagnetic problems. Namely, he derived all the basic equations, created and tested computer programs in *MATLAB* package, performed all numerical calculations, and participated in interpretation and discussion of numerical results related to the physical effects accompanying radiation and absorption of electromagnetic waves.

Presentation of the results. The thesis results were presented and discussed at the following national conferences and seminars: “Millimeter wave physics and technology” at IRE NAS, “Integral equations of electromagnetics” at the Kharkiv National University of Radio Electronics, at the Kharkiv Young Scientist Conferences on Radiophysics in 2001, 2002, 2004 and also at the following international conferences: Mathematical Methods in Electromagnetic Theory (MMET*98, MMET*2000, MMET*04), Kharkiv, Ukraine, 1998, 2000, Dnepropetrovsk, Ukraine, 2004, Optique Hertzienne et Dielectriques (OHD-99), Besanson, France, 1999, General Assembly of URSI, Toronto, Canada, 1999; Journee Internationale de Nice de les Antennes (JINA-02), Nice, France, 2002; International Kharkiv Symposium of Physics and Engineering of Microwaves, Millimeter, and Sub-Millimeter Waves (MSMW-04), Kharkiv, Ukraine, and Asia-Pacific Microwave Conference (APMC-2006), Yokohama, Japan, 2006.

Publications. Based on the obtained results, 4 journal papers [1-4] and 9 conference papers [5-13] have been published.

Structure and size of the thesis. The paper includes introduction, 4 chapters, conclusions and a list of literature sources which have been used. The total thesis size amounts 133 pages, from them 7 pages are the list of the references (74 titles).

THESIS CONTENTS

In introduction the timeliness of the considered topic is grounded, the aim and the tasks of the investigation are formulated, and the general characteristics of thesis are presented.

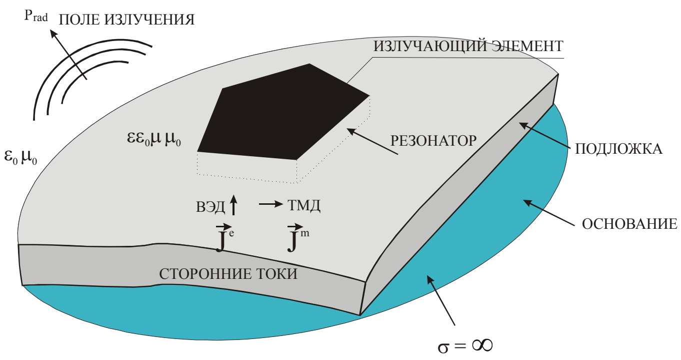

Fig.1 Conformal MSA on a curved surface

Chapter 1 is dedicated to a literature review on the thesis subject.

The *first Section* deals with a review of the basic principles of operation and also with the history of development of MSAs. These antennas were proposed in the late 1950s and underwent a very considerable development in the 1970-1990s. The principle of operation of the elementary MSA consists in the sharp increasing of the radiating ability of a coaxial probe or a slot in the metal screen due to the resonance in the cavity between a planar printed radiating element and a metal ground (Fig. 1). The dielectric substrate plays the role of constructive element which gives solidity to the resonator. This dielectric substrate can host a large number of elementary patches in the form of MSA united in the phased arrays.

In the *second Section*, the principal existing CAD methods for the modeling of MSAs are considered. It is possible to point out to two large groups of such methods, namely the simplified physical-model methods and direct numerical methods. E.g., the method of equivalent transmission lines and the cavity method based on the equivalence principle belong to simplified methods. The method of moments (MM) and finite-difference time-domain method (FDTD) belong to the direct numerical methods. In FDTD, the time and coordinate differential operators are substituted with the corresponding finite differences. The advantage of FDTD is flexibility in the application to arbitrary-shape structures, especially in the inner electromagnetic problems. The disadvantages of this method are more exposed in the open structures analysis when it is necessary to introduce artificial absorbing boundary conditions on the virtual boundary of the computational window. This method does not possess guaranteed convergence and can be used mainly for calculations of antennas with fixed parameters and frequency. Moreover it requires large expenditures of computing time. Another direct numerical method, MM, is more economic than FDTD however has considerable limitations as well. MM solution algorithm includes the following steps: at the first stage the integral equations (IE) for surface currents or polarization currents are derived from the Maxwell equations and boundary conditions on the analyzed scatterers, at the second stage these equations are solved directly[3]. To this end the unknown current function is represented in the form of series in terms of the some basis functions. The effectiveness of MM very strongly depends on the choice of the basis functions. The convergence takes place in the case of good luck however in the general case there are no

[3] A.A. Kishk, Analysis of spherical annular microstrip antennas, *IEEE Trans. Antennas Propagation*, 1993, vol. AP-41, pp. 338-343.

theorems which guarantee the convergence or even the existence of the exact solution of the discrete (i.e. matrix-type) MM equations since they are the first kind equations. There is no method which allows estimating the value of error linked to matrix truncation, namely there is no rule which allows determining how many equations is necessary to take for achieving a desired number of correct digits in the numerical solution. For example, it is known that both MM and FDTD lead to considerable errors near to the high-quality resonances. It is a noticeable disadvantage in our case because MSAs are essential resonance devices.

The *third Section* is dedicated to the survey of the main types, properties and peculiarities of practical application of specific MSAs, namely *conformal* printed ones located on the curved surfaces and substrates.

In the *fourth Section*, the foundations of the method of analytical regularization (MAR) is considered. This method is used systematically in the thesis. In this sub-section the advantages of MAR in the problem of the spherical conformal MSA analysis are discussed. MAR allows overcoming the earlier mentioned methods disadvantages and obtaining the reliable information because MAR has guaranteed convergence. It means that this method allows building the effective numerical algorithm and does not request considerable expenditures of computing time. The method foundations were established in the 1970s in the paper[4] for the scalar (acoustic) scattering problem. Later MAR was extended to the electromagnetic vector scattering problems in [5],[6],[7]. In brief, this method is based on the fact that similar problems for a zero-thickness perfectly electrically conducting (PEC) spherical disk in static field have explicit analytical solutions or can be reduced to the Fredholm second kind equations. In a general case, the electromagnetic field is represented by two auxiliary functions: electric *U* and magnetic *V* Debye potentials, which satisfy Helmholtz equation and Sommerfeld radiation condition. By expanding these potentials into series in terms of the spherical wave functions it is possible to reduce the problem to the dual series equations (DSEs) in associated Legendre functions. Depending on the symmetry of the initial field one set of DSEs or two coupled sets of DSEs appears. Analytical regularization procedure of DSEs is based on the extraction from DSEs some part which corresponds, e.g. to the static problem for a PEC disk with angular size $2\theta_0$ in free space. To do this, based on the known asymptotic behavior of the spherical Bessel and Hankel spherical functions for the fixed arguments and index $n \to \infty$, an asymptotically small when $k_0 c / n \to 0$ parameter $\varepsilon_n(k_0 c) = O(k_0 c / n)$ is extracted from the DSEs weight functions, where $k_0 = \omega / v = 2\pi / \lambda_0$, ω is cyclical frequency, v is the velocity of light, and c is the radius of disk curvature. After this DSEs take the following canonical form:

$$\begin{cases} \sum_{n=1}^{\infty} X_n P_n^1(\cos\theta) = \sum_{n=1}^{\infty} X_n \varepsilon_n P_n^1(\cos\theta) \quad \theta \in [0, \theta_0), \\ \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} X_n P_n^1(\cos\theta) = \sum_{n=1}^{\infty} (2n+1)\alpha_n P_n^1(\cos\theta) \quad \theta \in (\theta_0, \pi], \end{cases} \tag{1}$$

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[4] A.M. Radin, V.P. Shestopalov, Diffraction of waves on a sphere with an opening, *Soviet Physics Doklady*, 1973, vol. 212, no 4, pp. 838-841.

[5] S.S.Vinogradov, On the reflectivity of a spherical shield, *Radiophysics and Quantum Electronics*, 1983, vol. 26, no 1, pp. 78-88.

[6] R.W. Ziolkowski, W.A. Johnson, Electromagnetic scattering of an arbitrary plane wave from a spherical shell with a circular aperture, *J. Mathem. Physics*, 1987, vol. 28, no 6, pp. 1293- 1314.

[7] Y.V. Svishchev, Y.A. Tuchkin, Regularization of the diffraction boundary-value problem on the electromagnetic wave diffraction by a perfectly conducting spherical segment, *J. Comput. Math. and Mathem. Physics*, 1998, vol. 38, no 2, pp. 262-276.

where known coefficients $\alpha_n \to 0$ if $n \to \infty$, $P_n^1(\cos\theta)$ are associated Legendre functions, and X_n are unknowns.

Since the second of DSE contains the term behaving as $O(n^{-1})$, than the first one should be integrated in the variable θ and reduced to the form containing Legendre polynomials. Then the polynomials and associated Legendre functions are replaced by their representations in the form of the Meller-Dirichlet integrals for transforming them to the set of homogeneous Abel integral equations (IEs). Making use of these IE properties it is possible to reduce them to the other DSEs in terms of trigonometric functions and to apply for them inverse discrete Fourier transformation [4]. By means of this procedure the inversion of the static part of initial DSE (1) is achieved. The result takes form of infinite-order matrix equation of the second kind, which can be presented in the operator form as

$$(I + A)X = B, \tag{2}$$

where $I = \{\delta_{mn}\}_{m,n=1}^{\infty}$, $A = \{A_{mn}\}_{m,n=1}^{\infty} = \{\varepsilon_n Q_{nm}^{(1)}\}_{m,n=1}^{\infty}$, $B = \{B_m\}_{m=1}^{\infty} = \left\{\sum_{n=1}^{\infty} n(n+1)\alpha_n(\delta_n^m - Q_{nm}^{(1)})\right\}_{m=1}^{\infty}$,

$$Q_{nm}^{(1)}(\theta_0) = Q_{nm}(\theta_0) - \frac{Q_{0m}(\theta_0)Q_{n0}(\theta_0)}{Q_{00}(\theta_0)} \quad \text{and} \quad Q_{nm}(\theta_0) = \frac{\sin(m-n)\theta_0}{m-n} + \frac{\sin(m+n+1)\theta_0}{m+n+1}.$$

Since $\sum_{m,n=0}^{\infty} |A_n|^2 < \infty$, than (2) is an operator Fredholm equation of the second kind in the space of numerical sequences l_2 ($X \in l_2$ if $\sum_{n=0}^{\infty} |x_n|^2 < \infty$) under the condition that $\{\alpha_n\}_{n=0}^{\infty} \in l_2$. These equations are well known and their theory guarantees the solution existence in the mentioned space if only the uniqueness of solution is provided by their equivalence to the initial boundary-value problem for Maxwell equations (Fredholm alternative). Approximate solution of (2) can be obtained after truncation of the infinite system up to finite order N, and its error rapidly decreases when N grows, so that this error is bounded only by the digital precision of the computer used.

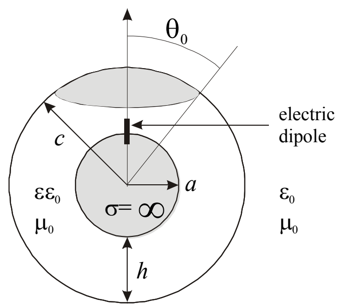

Fig. 2 Geometry of a spherical-disk MSA excited by a RED

In **Chapter 2**, the axially symmetrical problem of the wave radiation by a spherical disk MSA excited by an elementary radial electric dipole (RED) is considered. This dipole is a model of antenna feeding with the aid of coaxial probe (i.e., open coaxial cable).

The *first Section* is dedicated to the problem statement and geometry description – see Fig. 2. MSA has a spherical PEC ground of the radius *a* and the substrate of the radius *c* and the thickness *h* with the relative permittivity ε . On the outer surface of the substrate there is a PEC zero-thickness spherical disk of the angular size $2\theta_0$. The problem has been considered for an arbitrary location of the exciting RED on the axis *z* at the distance *b* from the centre of the spherical ground ($a \le b < c$). However if we take $b = a$ in the final equations, we obtain the problem solution for the dipole sitting on the surface of the PEC sphere.

In each case a complete set of conditions involved into the boundary-value problem of the wave radiation must provide the uniqueness of its solution. This set includes Maxwell equations in the whole space out of the conductors and boundaries, the boundary conditions on the PEC spherical ground and PEC disk, the tangential field components continuity conditions on the dielectric boundaries, i.e. on the surface which supplements the disk to complete sphere of the same radius, Silver-Muller radiation conditions, and the condition of local integrability of the field energy. In the rotationally symmetric case of axial RED excitation the problem considerably simplifies because for complete description of electromagnetic field it is enough to introduce only one auxiliary function - electric potential $U(r,\theta,\varphi)$, and magnetic one is absent, $V \equiv 0$.

In the *second Section* the procedure of the boundary-value problem reduction to DSE in terms of associated Legendre functions is presented. It is realized by substituting the electromagnetic field series expansions to the mixed boundary conditions. After some algebra, DSE are cast into the form most convenient for the further derivations.

The *third Section* is devoted to the analytical regularization of DESs. The regularization is realized by the extraction of the part of the DSE operator, which corresponds to the static problem for a PEC spherical disk in free space, from the full-wave problem operator. Then the first equation is integrated in θ for the balancing of the series properties with the second equation, and further the Meller-Dirichlet transformation is applied to the polynomials and associated Legendre functions for the transformation of each series equation to a homogeneous Abel IEs. By making use of these IE properties it is possible to simplify considerably the problem and to pass from the IE set to the DSE set in terms of trigonometric functions [5]. The resulting infinite-matrix equation of the second kind in the operator form looks like (2).

In the *fourth Section* the formulas are derived for such basic physical characteristics of the spherical MSA as the radiation pattern (RP) in the far zone, the total radiated power, the radiation resistance, and also the directivity. All these values are given in the form of the series with coefficients depending on unknowns solving the mentioned above matrix equation and spherical wave functions.

The *fifth Section* is devoted to the presentation and discussion of the numerical results. For the computation algorithm verification, the behavior of the relative error of computation that is caused by the matrix truncation is investigated. This value is determined by the formula

$$e(N) = \max_{n \le N} \left| X_n^{N+1} - X_n^N \right| \left(\max_{n \le N} \left| X_n^N \right| \right)^{-1} \tag{3}$$

and shown in Fig. 3 as a function of the matrix truncation order N for several values of the electrical size of MSA.

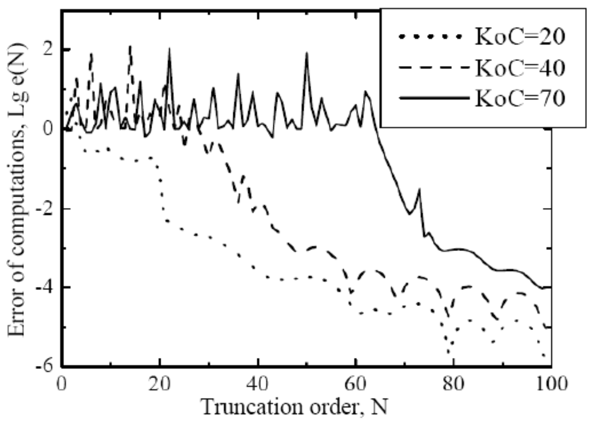

Fig. 3 Relative computational error versus the matrix size for h/c=0.1, θ_0=18°, ε=1.3.

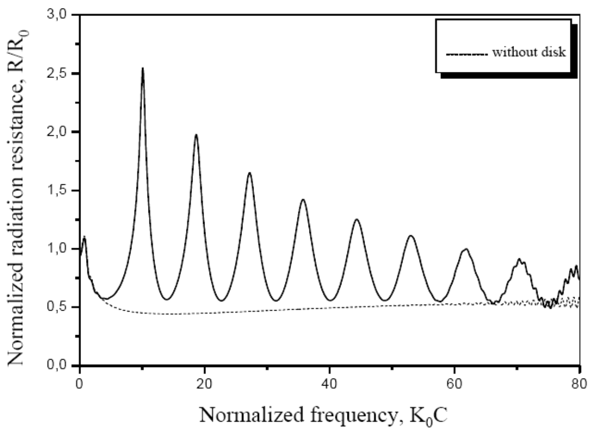

Fig. 4 Normalized radiation resistance versus normalized frequency, RED excitation. h/c=0.02, θ_0=18°, ε=1.3.

One can see that the error value depends on the electrical size of antenna, $k_0 c\sqrt{\varepsilon}$, and on the relative thickness of substrate, h/c. At the same time there exists such a value of $N > k_0 c\sqrt{\varepsilon}$ after which a sharp decrease of the error starts.

Therefore, for example, for achieving the relative accuracy of 10^{-3} during the calculation of coefficients X_n it is necessary to take the matrix truncation order as $N \geq k_0 c\sqrt{\varepsilon} + c/h + 10$.

Summarizing the data of these estimations it is possible to formulate that the radiation resistance behavior of the considered MSA excited by RED has rather complicated character. This behavior is determined by such factors as (*1*) low-frequency resonance of the spherical ground, (*2*) sharp resonances in the cavity between the ground and the disk, and also (*3*) small-amplitude periodical resonances in the spherical dielectric substrate that are explained by the standing quasi-surface waves having the same nature as well-known “whispering gallery modes”.

The field analysis in the far zone shows that RPs have conical shape with the zeros along the symmetry axis (θ=0°, 180°). This is caused by the fact that RED which excites MSA does not generate the electric field directed along its axis. At the lower frequencies ($k_0 c < 2$) the radiation has a strongly evident dipole character with predominant sidelobes radiating in the directions 90° and 270°. If the frequency is growing, the resonances of the TM_{0m0} type are excited in the open cavity between the spherical disk and the spherical ground conductor. The number *m* of resonance type corresponds to the number of variations in the current function on the disk radius, and the same number of conical beams is observed in RP. If the frequency increases still further and reaches the value approximately corresponding to $k_0 h\sqrt{\varepsilon} \approx \pi/2$, than periodical resonances are excited in the substrate in the shape of the oscillations of the “whispering gallery mode” type. It is necessary to note that besides the radiation into the forward (regarding to the disk) half-space, the analyzed antenna may have strong “parasitic” radiation into the backward half-space, in certain regimes. In fact, the main beam (RP maximum) “keel over” to the backward half-space always takes place if increasing the frequency. This phenomenon is caused by the oscillations of the “whispering gallery mode” type and by the currents generated due to these waves on the back side of the ground sphere.

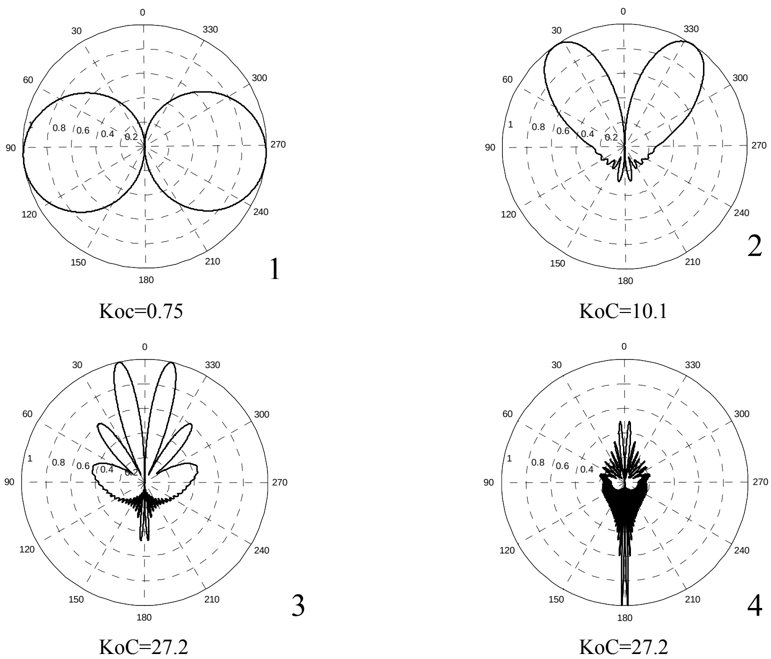

Fig. 5 Normalized RPs in the ground-sphere resonance, TM_{010} and TM_{020} cavity resonances, and in the whispering-gallery-mode range (see Fig. 4), for *h/c*=0.02, θ_0=18°, ε=1.3.

Concerning the antenna radiation dependence on the disk angular size, $2\theta_0$, relative substrate thickness, h/c, and its permittivity, ε, it is possible to note the following:

- When increasing the disk angular size θ_0, the resonances associated with the cavity under the disk move to the lower frequency range, get higher Q-factors, and their amplitudes rise. However the variation of this parameter has a little influence on the resonances associated with the spherical ground and the “whispering gallery mode” resonances.
- Increasing of the permittivity ε forces the disk resonances to move to the lower frequency range, their amplitudes rise, the beginning of the region of the “whispering gallery mode” resonances also moves to the lower frequencies, and the ε variation has very small influence on the resonance associated with the spherical ground.
- Decreasing of the relative substrate thickness h/c leads to the spherical disk resonances growth, their Q-factors rise, and the range of “whispering gallery mode” resonances begins from the shorter waves.

It is possible to obtain certain useful information investigating the dependence of the RP main beam direction on the normalized frequency, k_0c. This information allows revealing such operating regimes of antenna when it radiates to the forward or backward half-spaces due to the proper choice of MSA dimensions and dielectric parameters of substrate.

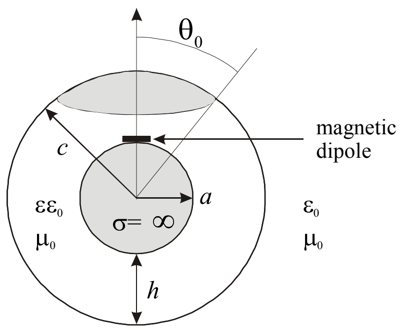

Fig.6 Geometry of a spherical-disk MSA excited by a TMD

In **Chapter 3**, the problem of radiation of waves by a spherical disk MSA excited by an elementary tangential magnetic dipole (TMD) located at the axis *z* (Fig. 6) is considered. This dipole corresponds to the feeding of antenna by a slot in the ground conductor.

The *first Section* is dedicated to the problem statement. The geometry of the structure is similar to the one considered in Chapter 2, with the only difference that, on the surface of the PEC ground sphere, a TMD is placed instead of the RED. The essential distinction of this problem from the previous one is that in this case the electromagnetic field depends on the azimuth coordinate φ. As in Chapter 2, the corresponding conditions at the material boundaries, conductors, infinity and spherical disk edge are formulated for providing the uniqueness of the solution. In this case all six components of the electromagnetic field are included into these conditions.

In the *second Section*, the boundary-value problem is reduced to the DSEs. Here, the both of Debye potentials (electrical one *U* and magnetic one *V*) are used, as all electric and magnetic components of the field are present. These sets of equations are coupled to each other by two constants, which correspond to the fact that the spherical harmonics of the E and H-type do not scatter independently like this is in the closed-sphere case.

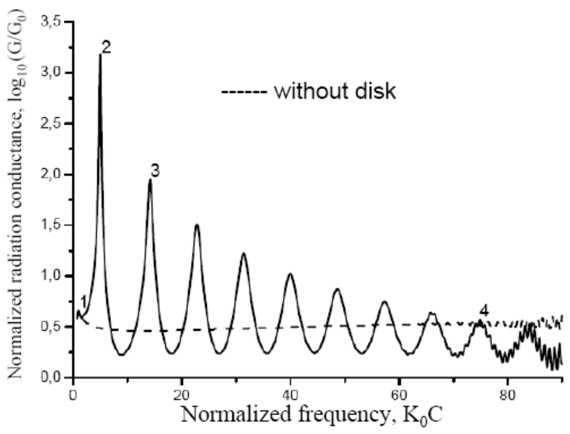

Fig. 7 Normalized radiation conductance versus normalized frequency, TMD excitation, k_0c, *h/c*=0.02, θ_0=18°, ε=1.3.

In the *third Section*, the regularization procedure of the coupled DSE sets is performed. Knowing asymptotic behavior of the spherical Bessel functions it is possible to extract two parameters, ε_n and μ_n, in the weight functions that are small when $n \to \infty$, and reduce DSEs to the form similar to (2) but with two additional coupling constants. Further, Meller-Dirichlet transformation for the associated Legendre functions and the tangent and cotangent functions is applied. This allows obtaining two coupled sets of the homogeneous Abel IEs and further two coupled DSEs with trigonometric functions. Then the standard steps are followed similarly to the ones described in Chapters 1 and 2. These steps are as follows: the balancing of the series behavior in the equations (by making use of the differentiation in θ) and the application of the inverse Fourier transformation. The main difference of given equations from the ones found in Chapter 2 consists in the necessity of finding two unknown constants, by means of which the sets of equations for the expansion coefficients of electric and magnetic fields are coupled. The final coupled matrix equation of the second kind takes form as

$$\begin{pmatrix} I + A^{(ee)} & A^{(em)} \\ A^{(me)} & I + A^{(mm)} \end{pmatrix} \begin{pmatrix} X^{(e)} \\ X^{(m)} \end{pmatrix} = \begin{pmatrix} B^{(e)} \\ B^{(m)} \end{pmatrix}, \tag{4}$$

where the elements of the matrix blocks and the matrix right-hand parts possess the same properties as the elements of (2). Therefore (4) is an operator Fredholm second kind equation in the space $l_2^2 = l_2 \times l_2$ and can be solved by the truncation method.

The *fourth Section* deals with the derivation of the expressions for the principal antenna characteristics in the form of the series with coefficients depending on the unknowns satisfying (4). These principal characteristics are two RPs in the main planes of the analyzed MSA (dipole plane, $\varphi = 0$, and normal to the dipole plane, $\varphi = 90^{\circ}$, or H-plane and E-plane), partial directivity factors in these two planes, and also the power and the conductance of radiation.

In the *fifth Section*, the computational error caused by the truncation method is studied and principal numerical results are discussed. The difference of the error evaluation from that found in Chapter 2 lies in the fact that it is necessary to calculate this value taking into account the coupling of matrix equations, i.e. for the vector $\bar{X} = \{X^{(e)}, X^{(m)}\}$. The error behavior as a function of the truncation order *N* is similar to its behavior in the previous problem. To achieve the relative accuracy of 10^{-3} in the solution of (4), one has to take the truncation order of every matrix block as $N \geq k_0\sqrt{\varepsilon}c + c/h + 10$.

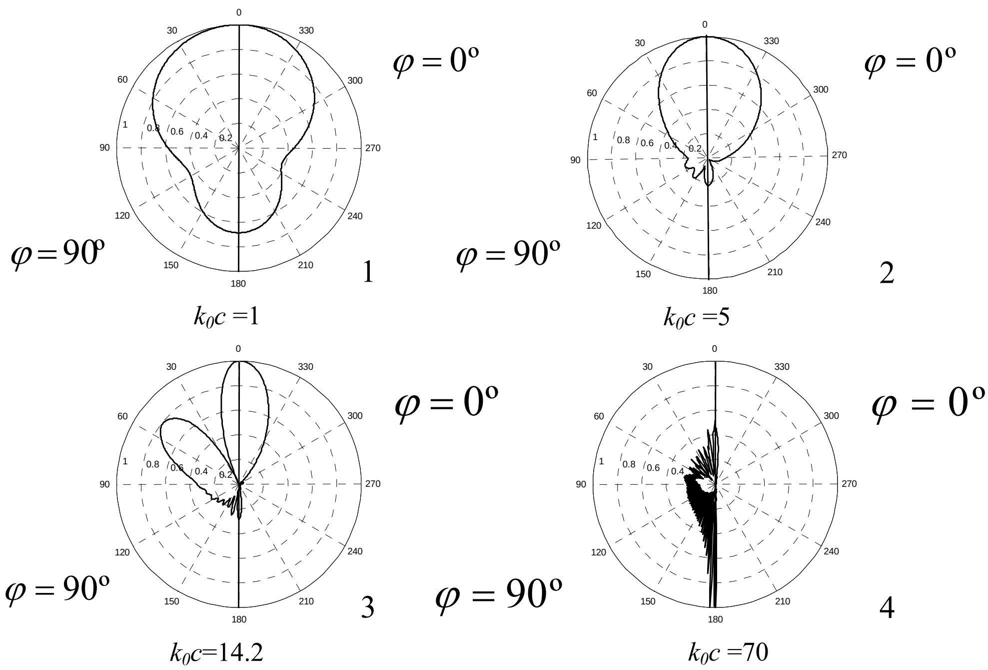

Fig. 8 Normalized RPs in the ground-sphere resonance, quasi-TM_{010} and TM_{020} resonances, and in the whispering-gallery-mode range (see Fig. 7) for *h/c*=0.02, θ_0 =18°, ε =1.3.

In general, when analyzing the radiation of our MSA excited by TMD one observes the same phenomena as in the case of antenna excited by RED, namely: (*1*) the low-frequency "dipole" resonance of PEC ground sphere, (*2*) the resonances in the cavity under the spherical disk, and (*3*) the high-frequency resonances of the quasi-surface waves of "whispering gallery mode" type. These phenomena have the same regularities as in the previous problem that is demonstrated by the plots of the normalized radiation conductance versus the normalized frequency.

From the RP analysis, one can see that the analyzed conformal MSA is able to radiate the main beam in the direction of the symmetry axis into the forward half-space, i.e. at θ=0° (Fig. 8). On the whole, the radiation of the antenna excited by TMD has more directional character than the same antenna excited by RED. The plots of the direction of the RP maximum as a function of the normalized frequency under various disk and dielectric substrate parameters allow revealing the regimes of the predominance of the forward and backward radiation.

In particular, when the substrate is thin enough the dominant factor is the cavity resonances of the quasi -TM_{1m0} type (m=1,2,…), where the radiation power exceeds the low-frequency resonance of the PEC sphere by 2-3 orders of magnitude. In Fig. 7 we have marked, by numbers, the points where the RPs shown in Fig. 8 are computed. Each sub-figure of the latter contains the information about RP behavior in the both of the main planes. When the frequency comes to the next cavity resonance, a new sidelobe appears in RP in the E-plane. As in the previous axially-symmetric problem, at the high enough frequencies the radiation goes predominantly into the backward half-space, i.e. the RP "keel over" happens, caused by the interference of currents associated with the "whispering-gallery modes" in the substrate.

Chapter 4 deals with investigation of the electromagnetic wave absorption by a double-layer highly lossy dielectric sphere. The geometry of this problem is similar to that considered in Chapter 2, however the inner domain of sphere is dielectric instead of PEC metal, and a RED is located above the PEC spherical disk. The interest in this structure is caused by the observation that it can model a partially screened biological object in the presence of the radiating antenna - if electrophysical parameters of the dielectrics are assumed close to those of the biotissues. In fact, we keep in mind that this is a simplified phantom of the human head protected by the metal helmet equipped by a short-wire antenna.

The *first Section* contains the statement of considered problem which close in many respects to one studied in Chapter 2. The main difference is that RED is placed at some distance above the external surface of the PEC spherical-disk screen (see Fig. 9) and this distance cannot be reduced to zero. Besides, in the computations we consider the dielectric layers of the sphere are absorptive ones, i.e. we take their dielectric permittivities as complex values, i.e. $\varepsilon_{1,2}=\varepsilon'_{1,2}+i\varepsilon_{1,2}''$, where $\varepsilon_{1,2}''=i\sigma_{1,2}/\omega$, and $\sigma_{1,2}$ are conductivities.

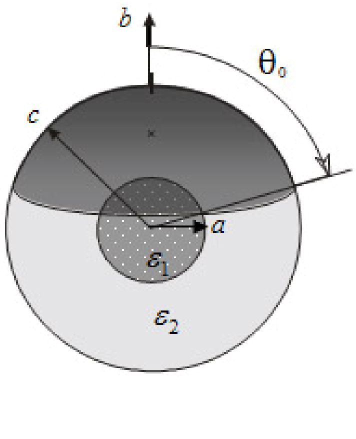

Fig. 9 Partially-screened double-layer dielectric sphere in the radiation field of a RED placed at the axis of symmetry above the spherical-disk screen.

In the *second Section*, the analytical regularization of this problem is realized. It includes all steps that are found for the MSA excited by RED (see Chapter 2). As a result we obtain a matrix equation of the second kind in the form like (2), from which the expansion coefficients of the field components into the series in associated Legendre functions can be found. The difference from the matrix equation obtained in Chapter 2 consists in the new coefficients $\varepsilon_m(k_0c, a/c, \varepsilon)$ and $\alpha_m(k_0b)$, and condition $b>c$ that follows from the analysis of the right-hand part elements.

The *third Section* contains the derivation of the main antenna characteristics: RP, the power radiated into the outer space, the power absorbed inside the layered sphere, and also the total input antenna resistance, which contains the radiation resistance and the absorption resistance ($R_{input} = R_{rad} + R_{abs}$). We use the complex Poynting theorem for the calculation of the radiated power and radiation resistance to avoid of the integration of the products of Bessel and Hankel function with complex arguments. This allows reducing the indicated values to the flux of the normal component of the Poynting vector through the surface of absorbing sphere. We have computed these characteristics for the dimensions and electric parameters of sphere close to the average parameters of the human head; the frequency range has been chosen to cover the operational frequencies of the standard devices of mobile communication systems.

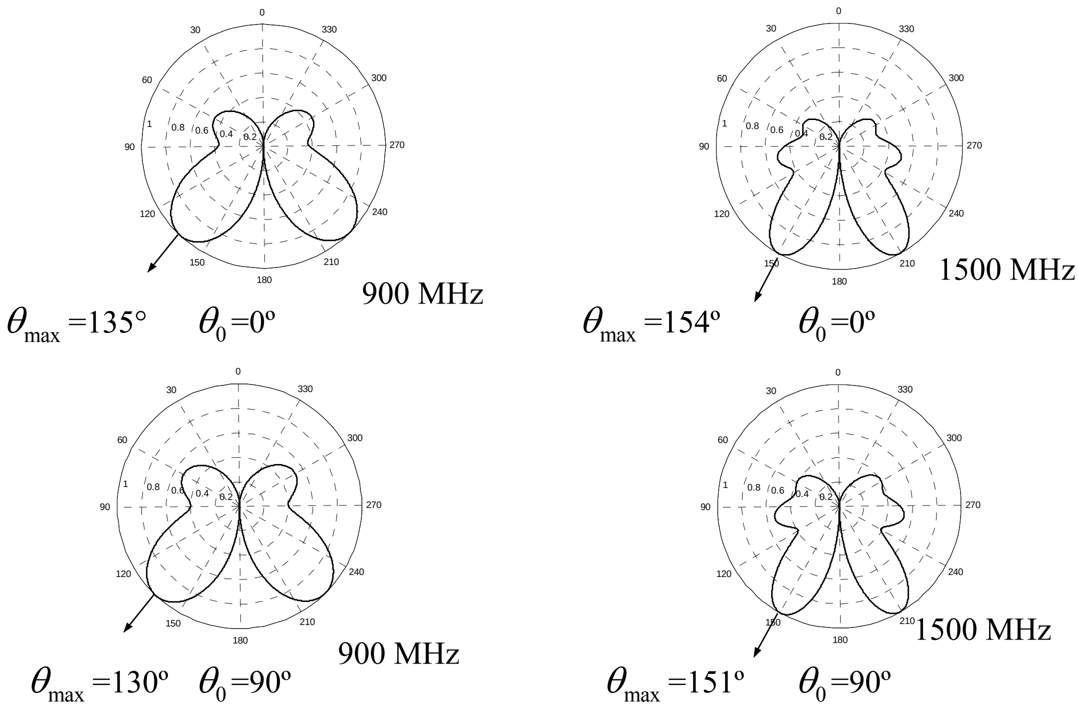

Fig. 10 Normalized RP of the dipole in the presence of a partially screened layered sphere having the following parameters: c =10 cm, *h*=3 mm, θ_0 =0° and 90°, ε_1 =52.7, σ_1 =1.05 Sim/m, ε_2 =26.1, σ_2 =0.45 Sim/m (for the frequency of 900 MHz) , ε_1 =46, σ_1 =1.65 Sim/m, ε_2 =26.1, σ_2 =0.71 Sim/m (for 1500 MHz).

In the *fourth Section*, the numerical results are given for the characteristics of the dipole antenna radiating in the presence of absorbing dielectric sphere. The normalized RPs are presented in Fig. 10. They are close to the RPs of the same dipole in the free space since the wavelength is much larger than the radius of the spherical disk and absorbing sphere. However the radiation into the lower half-space prevails because the permittivity and the conductivity of the sphere are much larger than those for the free space.

The plots in Fig. 11 show the power absorbed in the two-layer phantom versus the frequency for unprotected sphere and for four different sizes of the covering metallic helmet. It is seen that even a small screen between RED and sphere is an effective protection. The plots in Fig. 12 demonstrate how much the level of absorption in the sphere decreases when the angular size of the PEC screen increases, from a bare dielectric sphere to completely screened one. For example, a hemispherical screen reduces the power absorbed in the sphere with parameters of the human head tissues in 100 and more times.

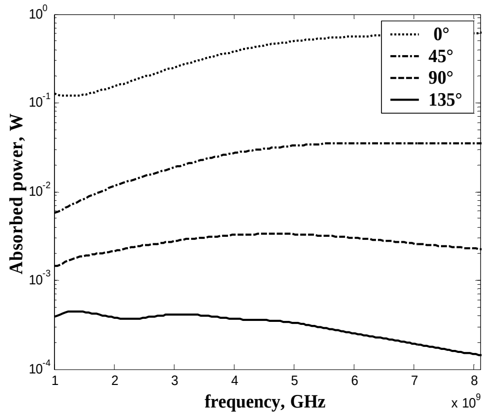

Fig. 11 Power absorbed in the phantom vs. frequency. Dipole parameters: I_0=0.1 A, l=2 cm, sphere parameters: h=3 mm, c=10 cm, ε_1=53, σ_1=1.5 Sim/m, ε_2=23, σ_2=0.6 Sim/m, for various angular sizes of the screen: θ_0=0°, 45°, 90°and 135°.

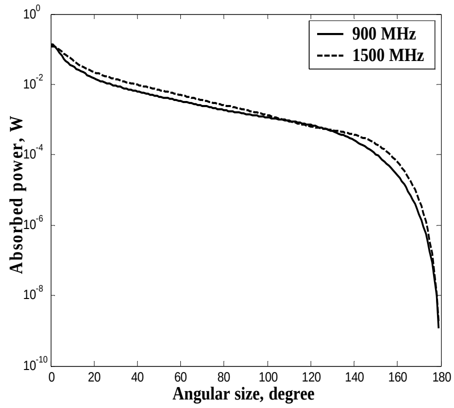

Fig. 12 Power absorbed in the phantom as a function of the screen angular half-width, θ_0, for the same geometrical and material parameters as in Fig. 11 and two values of the frequency, 900 MHz and 1500 MHz.

These results allow choosing the angular size of the screen for decreasing the level of the absorbed power to a required value at a given frequency. For comparison the same characteristic is presented for the same sphere without a screen. Besides of considerable reduction of the level of absorbed power, it is possible to notice the absence of the resonance phenomena even if the open resonator formed by the spherical disk tends to a metal sphere with a small hole. This is explained by the relatively high absorption in the materials simulating the human head tissues, especially the brain.

Conclusions

1. The radiation of electromagnetic waves by the spherical conformal MSAs has been investigated in the rigorous problem statement by making use of the MAR, which generates algorithms having guaranteed convergence and controlled accuracy.
2. The software package has been developed in *MATLAB* shell. This package implements the effective algorithms of the MSA computation that are cheap in terms of computer time and memory expenditures.
3. Basic physical characteristics of the considered MSAs have been analyzed. They are RP in the far zone, the radiation resistance (or conductance), the directivity, and the RP main beam direction. It has been studied how the relative thickness of the dielectric substrate, h/c, its dielectric permittivity, ε, and spherical disk angular size, $2\theta_0$, effect on the far-field radiation and on the input resistance (conductance) of antenna.
4. It has been shown that complicated resonance character of the radiation of spherical conformal MSAs is caused by the three phenomena: (1) weak low-frequency resonance of the ground sphere, (2) intensive high-Q resonances in the cavity under the spherical disk, and (3) small high-frequency periodic resonances due to the standing waves of the "whispering-gallery-mode" type in the dielectric substrate.
5. The study of RPs of the spherical MSA excited by RED and TMD has shown that they have a "dipole" character in the resonance of the ground sphere and radiate mainly in the forward half-space in the cavity resonances; here the number of sidelobes corresponds to the number of the current variations along the disk radius. However, if the frequency exceeds certain value, which depends on the substrate thickness and dielectric constant, then a "keel over" of RP takes place. This effect is caused by the "whispering-gallery-modes" that induce strong currents on the back side of the ground sphere.

6. The radiation and absorption of electromagnetic power of a dipole antenna in the presence of a partially screened double-layer dielectric sphere has been studied. This structure serves as a simplified phantom of a dipole antenna user head protected with a metal helmet. It has been shown that the absorption in the sphere having electrophysical parameters of the brain (inner domain) and averaged skin-bone tissue (outer layer) can be lowered in over 100 times by using a hemispherical helmet.

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4. Radchenko V.V. Absorption of the electromagnetic energy radiated by dipole antenna in a partially screened double-layer dielectric sphere // *Kharkiv National University Digest*. Kharkiv, KhNU Press. - 2005.- no 712.- pp. 62- 66 (in Russian).
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6. Radchenko V.V., Nosich A.I., Daniel J.-P. Exact mathematical model of conformal spherical disk antenna // *Proc. Int. Conf. Optique Hertzienne et Dielectriques (OHD-99)*. Besanson. – 1999. - pp. A21-A24.
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10. Radchenko V.V., Nosich A.I. Electromagnetic absorption by a partially screened double-layer lossy dielectric sphere axisymmetrically excited by an electric dipole // *Proc. Int. Symp. Physics and Engineering of Microwaves, MM, and Sub-MM Waves (MSMW-04)*. Kharkiv. - 2004. – pp. 308-310.
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12. V.V. Radchenko, Simplified model of electromagnetic energy absorption in the head of a dipole antenna user protected by a metal helmet // *Proc. Int. Conf. on Mathematical Methods in Electromagnetic Theory (MMET*04)*. Dnipropetrovsk. - 2004, - pp. 289-291.
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