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RADIATION AND FOCUSING OF ELECTROMAGNETIC WAVES BY CYLINDRICAL DIELECTRIC ANTENNAS

SUMMARY
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The study has been done in the Department of Computational Electromagnetics of IRE NASU.

Key words: dielectric rod antenna, Luneburg lens, extended hemielliptical (hemispherical) lens, boundary integral equations, analytical regularization, trigonometric Galerkin method, complex-source point, focusing.

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Scientific significance of the study follows from the fact that dielectric antennas (DAs) are widely used in today radio communication and remote sensing systems. Normally their dimensions are comparable to (although greater than) the wavelength – hence, both ray and modal phenomena exist together and interplay. However, common simulation tools based on "quasi-optical" methods, namely on geometrical and physical optics (GO and PO), do not allow one to study wave phenomena in realistic DAs in accurate and reliable manner. This prevents one from using these methods as a basis of accurate computer-aided design (CAD) tools in DA analysis and optimization. On the other hand, grid numerical methods like FDTD can hardly be used for the DA optimization due to their high requirements to computational time and resources, and problems with back reflections from the boundary of computational window. Hence, it is still significant to develop convergent, reliable and economic algorithms applicable to DA simulation. Such algorithms can be based on mathematically accurate treatment of the corresponding boundary-value problems for the Maxwell equations, namely on the boundary integral equation (BIE) methods, in combination with specific concept of analytical regularization, which guaranties a rapid convergence of discretized solutions.

Timeliness of research. Radio spectrum congestion, need for an ever-increasing bandwidth, and rapid development of THz systems have recently revived the interest in DA. Here, demand for mobile communications and cellular broadcasting have pushed radio communication first to microwaves and then to mm-waves. At these frequencies Ohmic losses introduce a penalty in metallic antennas, which may lead to additional manufacturing costs. Meanwhile the availability of high-performance low-loss dielectric materials makes DAs a viable candidate for such mm-wave applications as protected point-to-point communication systems, etc. In the sub-mm wave range, lens-type DAs are practically the main type of antennas used, due to their low cost and wideband performance. For example, development of so-called integrated lens DA has enabled one to improve the brightness of the printed source and thus became a major recent step ahead in such areas of mm-wave and sub-mm wave technology as time-domain spectroscopy, imaging, etc. All this justifies an intensive study of DAs based on the accurate numerical simulations.

Subject of research. In the thesis, two-dimensional (2D) models of several important from the practical point of view configurations of DAs are considered. They are a traveling-wave rod DA, which is used, e.g., as an improved feed of large reflector antennas, and two types of the lens antennas – discrete Luneburg lens used as main element of high-gain, multibeam and scanning antennas, and extended hemielliptical lens DA widely used in communications, THz spectroscopy, automotive radars, etc.

Relation to R&D projects and programs. This study has been done at the Institute of Radiophysics and Electronics of the National Academy of Sciences of Ukraine (IRE NASU), in line with the NASU research project "Theoretical and experimental research of the wave phenomena in microwave and mm-wave devices and systems" (2000-2003). It was also related to the following international research projects:

– «A beam scattering by a lossy circularly-layered dielectric cylinder with application to dielectric lenses and antenna radomes» (2000), Microwave Graduate Fellowship, IEEE Microwave Theory and Techniques Society.
– «Calculation and optimization of a dielectric rod antenna» (2001), TUBITAK – NATO Ph.D. Fellowship, jointly with Bilkent University, Ankara, Turkey.
– «Near fields of elliptic dielectric lenses» (2002), Institute of Telecommunications, Warsaw, Poland.

The aims of the study are:
- Development of numerically exact and rapidly convergent algorithms for the solution of the electromagnetic wave scattering by arbitrary shaped dielectric cylinders,
- Physical analysis, with these algorithms, of the wave fields of the simulated DAs and search for their optimal geometrical parameters.

In the study of the discrete Luneburg lens, our specific aims are:
- analysis of radiation characteristics and their improvement due to a proper choice of the aperture source parameters, edge illumination, lens size and number of layers,
- clarification of the effect of the whispering gallery modes (WGM) on the radiation characteristics.

In the study of the traveling-wave rod DA, our specific aims are:
- analysis of radiation characteristics and their improvement due to proper choice of the aperture source parameters and rod geometry,

In the study of the extended hemielliptical lens, our specific aims are:
- analysis of focusing properties of the elliptic lens illuminated by a plane wave,
- comparison of electromagnetic behavior of extended hemielliptical and hemicircular lenses,
- clarification of the effect of the lens extension size on the radiation characteristics.

Methods of research. To achieve the objectives, we apply mathematical methods, which guarantee accurate treatment of the corresponding boundary-value problems for the Maxwell equations in the open domains.

Thus, in the study of the radiation properties of circularly layered Luneburg lens we use the separation of variables method in combination with addition theorems for cylindrical functions. In the study of homogeneous DAs – rod antenna, and elliptical and extended hemielliptical and hemicircular ones – we apply (a) the method of elementary BIE in combination with the method of analytical regularization (MAR) and (b) the method of Muller BIE. Each of the BIE methods enables one to reduce the scattering problem to an infinite-matrix equation of the Fredholm second kind. Here, it has been demonstrated that MAR does not eliminate the drawback of the elementary BIE related to the loss of uniqueness of the solution at some discrete real-valued frequencies. This defect prevents elementary BIE to serve as uniformly reliable tool of analysis. Therefore the Muller BIEs, which are uniquely solvable, have clear advantage. For discretization of the either type of BIE, we use so-called trigonometric Galerkin scheme with the angular exponents as entire-domain basis functions.

Besides, the method of Complex-Source Point (CSP) is systematically used to simulate the beam-like fields of directive feeds. This is convenient approach when studying the DAs in the radiation mode. Indeed, by adding an imaginary part to a point (or line) source location in the real space, one changes its field from omnidirectional to directive. In the paraxial zone it possess the features of the Gaussian beam, and, what is more important, it is the exact solution of the Helmholtz equation at any point of the real space and even in the far zone. Plane wave is also considered as incident field important to study the focusability of DAs in the receiving mode.

The novelty of research is determined by the following original results obtained:
- Efficient numerical algorithm for the solution of the scattering by a smooth arbitrary shaped dielectric cylinder has been developed, based on the Muller BIEs with trigonometric Galerkin discretization and analytical regularization of singular kernels,
- Advantages of numerical algorithm based on the Muller BIEs have been demonstrated in comparison to the algorithm based on elementary BIE-MAR,
- Defect of the elementary BIEs related to the loss of solution uniqueness at discrete real-valued frequencies has been studied,
- A technique for the data interpolation to the “inaccessible” frequency intervals around the defect points of elementary BIE-MAR has been proposed,

- It has been shown that the optimal aperture-type feed location for a discrete Luneburg lens deviates from its outer surface and depends on the number of layers and lens size,
- It has been shown that WGMs excited in a discrete Luneburg lens may result, if the number of layers is small, in degradation of directivity as high as 10%,
- It has been shown that a discrete Luneburg lens DA should have 2 to 7 layers and its edge illumination by the beam-like feed field should be around -8 dB,
- It has been shown that a thin rod DA excited by an aperture source has an optimal length, which is a function of the wavelength and material parameters, and improper choice of the rod length may lead to the splitting of the radiation pattern main beam,
- Application of the Muller BIE method for the analysis of elliptic and elliptic-like lens DAs has demonstrated that their focal domains are complicated functions of the wavelength, lens geometry, and the angle of the plane wave incidence,
- It has been revealed that, in a 3-10 wavelengths lens, strong resonance effects exist together with ray-like features; this can lead to the new design of multiple-detector resonance receivers with enhanced sensitivity and scanning.

Practical impact. Use of the Muller BIE method with trigonometric Gelerkin discretization has enabled a development of numerical algorithm whose efficiency, in terms of tradeoff between CPU time, memory and accuracy is very high. Its universal convergence, which guarantees a desired accuracy for an arbitrary set of DA parameters, puts it far ahead of the other available CAD tools, which are commonly based on either ray tracing methods or FDTD.

Application of the developed CAD tool to DA simulation has also enabled us to do accurate and detailed analysis, and to deepen the knowledge of electromagnetic behavior of three most commonly used DAs. The obtained results contribute a great deal to better performance of mobile, indoor and space communication systems and other DA-based devices in microwaves and optics. Application of the developed CAD tool for systematic DA optimization may lead to the development of new DAs.

Author's personal contribution is proven by the number of journal and conference papers published in 1999-2003.

In the works [1,2,5-8,10,11], the author took part in obtaining the basic equations, performing the numerical simulation, and discussing the numerical results.

In the works [3,9,12-14], the author took part in development of the numerical algorithm, doing numerical simulations, and discussion of the results.

In the works [4,15-17], the author took part in development of theoretical approach, derivation of basic equations, writing and testing of the numerical code, doing numerical simulation, and interpretation of the results.

Presentation of results. Obtained results have been presented and discussed at the following scientific seminars: «Physics and Applications of MM Waves» IRE NASU (Prof. B.M. Bulgakov), «Integral Equations of Electrodynamics» Kharkov National University of Radio Electronics (Prof. A.G. Nerikh), «Mathematical Modeling and Computational Methods», North-East Division of NASU (Prof. Y.V. Gandel), Kharkov Young Scientists Conferences 2003, 2004, and the following international meetings: International Conference on Microwaves & Radar, Krakow, Poland, 1998; Wroclaw, Poland, 2000; International Conferences on Mathematical Methods in Electromagnetic Theory, Kharkov, Ukraine, 1998, 2000; International Conference on Antenna Theory and Technique, Sebastopol, Ukraine, 1999; IEEE AP-S & URSI International Symposium, Boston, USA, 2001 (2 papers); International Conference on Transparent Optical Networks, Krakow, Poland, 2001, Warsaw, Poland 2003; International Symposium on Physics and Engineering of MM and Sub-MM Waves, Kharkov, Ukraine, 2001; International Workshop on Optical Waveguide Theory and Numerical Modeling, Nottingham, UK, 2002; International Conference on Advanced Optoelectronics and Lasers, Alushta, Ukraine, 2003; European Microwave Conference, Munich, Germany, 2003.

Publications. Based on the obtained results, 4 journal papers [1-4] and 13 conference papers have been published [5-17].

DESCRIPTION OF THE THESIS

In **Introduction**, scientific significance of the considered problems is shown, the novelty of research is discussed, and the aims of the study are formulated.

Chapter 1 contains a review of the literature published within the scope of the research topic.

Section 1.1 reviews state-of-the-art of DA technology, principles of DAs construction, and their applications. [1,2] Broadly speaking, all DAs can be classified as either *resonator antennas* or *rod antennas* or *lens antennas*.

With a few exceptions, DAs are most useful at frequencies well above 1 GHz. They are usually lightweight, low cost, and have compact size and good corrosion properties. By the 1990's, the growth of the need for broadband wireless communication systems made the microwave frequency band too congested and unable to support the ever-increasing data-rate requirements. This resulted in a gradual shift of the operating frequency toward the mm-wave band. Here, resistive losses introduce a penalty in metallic antennas, which can be compound with increasing manufacturing costs. Therefore availability of high performance low-cast dielectric materials makes DA a viable candidate for mm-wave applications. Also in the 1990's, a rapid development of sub-mm wave and THz systems started, including time-resolved spectroscopy, imaging, and remote sensing. At these frequencies, DAs are the most advanced type of antennas due to essentially quasi-optical character of electromagnetic wave propagation and scattering.

In terms of sub-systems, applications of DAs are in advanced feeds for large reflector antennas, phased array elements, scanning and multibeam antenna modules, focusers for integrated-circuit receivers, and others. In most cases DAs are based on simple geometries: cylindrical, conical, spherical or hemispherical. More elaborate shapes are usually a variation of the previous geometries and mostly with axial symmetry.

Dielectric **rod antennas** are also called traveling-wave antennas as they use the effect of the field guidance along an infinite rod. Provided that rod is thin, only the principal mode can propagate. If an extended rod is abruptly terminated, this mode radiates in the forward direction. Therefore such antennas have normally small diameter and considerable elongation, with primary application, since the 1950's, in matching of open-ended waveguides with free space.

Lenses form an important subgroup of DAs with higher requirements to the cross-section geometries and usually are based on optical principles. They can be further classified as inhomogeneous lenses, usually of the simplest shape, and homogeneous lenses whose shapes vary greatly. The most popular, from the practical point of view, are DAs based on the Luneburg lens and integrated elliptical or elliptic-like antenna, respectively. Spherical Luneburg lens was introduced in 1944.[3] Then it was shown that, in the GO approximation, an incoming plane wave focuses to a point on the lens surface if its dielectric function depends on radius as $\varepsilon(r) = 2 - (r/a)^2$, $0 \le r \le a$, where a is the lens radius. Discrete version - circularly layered lens –

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[1] C. Salema, C. Fernandes, R.T. Jha, *Solid Dielectric Horn Antennas*, Boston, Artech House, 1998.

[2] E.G. Zelkin, P.A. Petrova *Lens Antennas,* Moscow, Sov. Radio, 1974. (*in Russian*)

[3] R.K. Luneburg, *The Mathematical Theory of Optics*, Brown University Press, 1944.

has been also considered, instead of inhomogeneous one, due to its simplicity as to the practical realization. Unlike optics, at microwaves such a wideband lens-type high-directivity antenna has been practically developed. A large number of papers have been devoted to the Luneburg lens analysis. These analyses were useful for the investigation not only the far field characteristics, but also of the structure and location of the focal domain, etc. In the 1990's, searching for applicable antenna concepts at mm-wave and higher frequencies in mobile communication systems, remote sensing, etc., renewed interest in multishell spherical lenses. Spherical symmetry of the lens and advanced position of a feed, which does not block the aperture, allow multi-beam scanning by placing an array of small horns around the lens.

Elliptic lens and its modifications occupy a specific place among homogeneous lenses. As GO predicts, if the eccentricity of the ellipse is related to the lens dielectric constant as $e = 1/\sqrt{\varepsilon}$, then all the rays of a parallel family that impinge on the lens interface above the middle section are collected in the focal point. In mm-wave and THz applications, extended hemielliptical or hemi-spherical lenses are widely used [1] in order to simplify the lens, feed and substrate coupling. Here, a great experience of development of microwave printed or slot antennas (3-30 GHz) have been used, resulting in the feeds as tiny printed elements backed with a flat substrate. The integrated-lens antennas became an elegant step forward in the DA technology as they provide highly directive antenna patterns, mechanical and thermal stability, suppression of the surface-wave losses, and capability of multi-beam formation. The wide attention they have been receiving recently is due to their capability of integration with electronics components such as detecting diodes, local oscillators and mixers.

In *Section 1.2*, the methods applicable to the analysis of DAs are discussed and compared. These are methods of GO and PO, as well as methods of volume and boundary integral equations (VIE and BIE), in combination with various discretization schemes and the method of analytical regularization (MAR). The role and the merit of MAR are explained. The advantages of the Muller BIE method are specified.[2]

Operation of different types of DAs is based on different principles. E.g., traveling-wave rod antenna is based on the guided-wave effects whereas lens antenna is based on ray ones. This determines engineering methods, which could be applied for the DA analysis. Besides, the internal structure of a DA is important as its homogeneity or piecewise homogeneity noticeably simplifies the analysis.

Lens antennas have been modeled with GO and PO that provides sufficient design of large DAs. Both methods are based on assumption of slowly varying amplitude of the field. Besides, GO is a scalar theory that means that polarization effects escape analysis. PO approximation is more adequate tool, as it enables one to describe diffraction effects, but similarly to GO it does not consider finite size of lens and edge diffraction. It is quite clear that full understanding of the properties of realistic DAs is impossible to achieve without application of full-wave methods. Indeed, assumption of slow amplitude variation fails to characterize the internal resonances especially if whole DA size is comparable to the wavelength, and simply cannot be applied for the focal domain and caustic analysis.

Besides, in the recent 15 years, the methods of finite elements and finite differences in time domain (FETD and FDTD) became very popular, due to simplicity of computer code development and universality as to the shape of the scatterer. These numerical approximations do not imply slow amplitude variation. However, it is known that FETD and FDTD methods are applicable to the internal problems solution whereas external ones, such as antenna simulation, may become a computational challenge. This is because external problem requires discretization of not only the scatterer but a large external domain as well. However, more fundamental

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[1] D.F. Filippovic, S.S. Gearhart, G.M. Rebeiz, Double slot on extended hemispherical and elliptical silicon dielectric lenses, *IEEE Trans. Microwave Theory and Techniques,* 1993, vol. 41, no. 10, pp. 1738–1749.

[2] C. Muller, *Foundations of the Mathematical Theory of Electromagnetic Waves*, Berlin, Springer, 1969.

problem is nonequivalence of discrete model to the mathematical problem because of staircasing of boundaries and violating the radiation condition at infinity.

That is why IE methods are attractive – their solutions accurately satisfy the boundary conditions as well as radiation condition. A scattering problem can be reduced either to volume or boundary IEs.[1,2] More effective algorithms, from the point of CPU time requirements, can be developed based on BIEs because it enables one not only to move from infinite domain to finite one (scatterer's boundary) but also to reduce the problem dimension. BIEs for a homogeneous scatterer can be derived in terms of single or double layer potentials or their linear combination. This results in BIEs of the Fredholm 1st kind with respect to unknown potential densities over the contour.[3] Such equations are often called elementary BIEs[4]. Unlike them, so-called Muller BIEs are of the Fredholm 2nd kind and can be obtained by appropriate choice of the coefficients in the combination of single and double layer potentials. The same can be achieved by using the 2nd Green's identity. To build a convergent algorithm, elementary BIE need a proper handling of the logarithmic singularities, which are eliminated with the MAR approach. In contrast, Muller BIE can be discretized in a variety of ways as their Fredholm nature guarantees convergence.

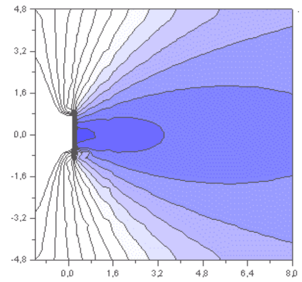

Fig. 1. CPS beam near-field intensity portrait (*kb*=5).

In *Section 1.3*, the ways are discussed of the modeling of beamlike wave simulating a directive incident field emitted by an aperture source. This is important part of analysis due to the fact that most DAs are excited by open-ended metallic waveguides, small horns, or printed radiators, i.e. not elementary dipoles. Here, the most accurate and attractive approach is to use a complex-source-point (CSP) field as a feed model (Fig. 1) with variable beam width. CSP field coincides with the Gaussian beam in the paraxial part of near zone and smoothly transforms into outgoing cylindrical wave in the far zone. At any point of the real space it satisfies the Helmholtz equation in rigorous manner. Such a model of a wave-beam has many advantages form both mathematical and physical points of view.[5]

Finally, the objectives of research and methods of their achievement are formulated based on the reviewed publications.

Chapter 2 is devoted to the analysis of radiation characteristics of discrete cylindrical Luneburg lens DA. Mathematically, this is a problem of electromagnetic field scattering by a circularly layered piece-wise homogeneous dielectric cylinder. Therefore the method of separation of variables, in combination with addition theorems for cylindrical functions, is used in its solution.

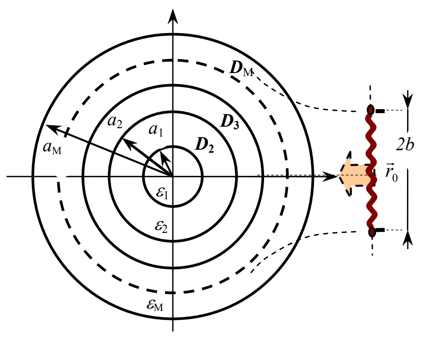

Fig. 2. Geometry of 2-D discrete Luneburg lens excited by a CPS beam.

In *Section 2.1*, a test example of the plane wave scattering by a homogeneous cylinder is considered, and reference results for the scattering cross-sections are computed. In *Sections 2.2* and *2.3*, two simple problems

[1] V.D. Kupradze, *Boundary Value Problems of Oscillation Theory and Integral Equations*, Moscow, GITTL, 1950.

[2] A.B. Samokhin, *Integral Equations and Iterative Methods in EM Scattering*, Moscow, Radio Svyaz, 1998.

[3] D. Colton, R. Kress, *Integral Equation Methods in Scattering Theory*, New York, Wylie, 1983.

[4] S. Amini, S.M. Kirkup, Solutions of Helmholtz equation in the exterior domain by elementary boundary integral methods, *Journal of Computational Physics*, 1995, vol. 118, pp. 208-221.

[5] L.B. Felsen, Complex-source-point solutions of the field equations and their relation to the propagation and scattering of the Gaussian beams, *Symp. Mathem.*, 1975, vol. 18, pp. 39-56.

associated with two-layer cylinders excited with CSP beams are considered: directivity degradation due to circular dielectric ring-like radome (CSP inside), and excitation of the whispering gallery (WG) resonances in a layered cylinder (CSP outside), respectively.

Finally, *Section 2.4* deals with discrete Luneburg lens symmetrically illuminated with a beam of a CSP located outside the lens. Our model of lens is a circular cylinder, each of whose M concentric layers has equal width, a/M, and dielectric constants taken according to the GO rule:

$$\varepsilon_s = 2-(s-1/2)^2/M^2, \quad s=1,2,...,M \qquad (1)$$

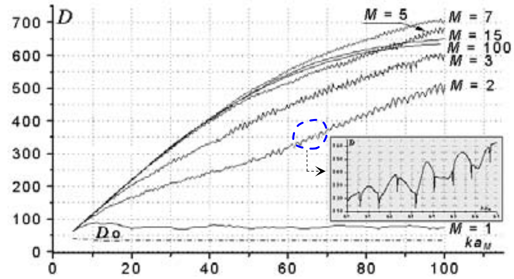

Fig. 3. Directivity of a discrete Luneburg lens fed by an E-polarized CSP beam versus normalized frequency parameter. D_0 is for CSP directivity in the free space. The insert is the zoom of a part of the curve for M=2.

Numerical analysis is focused on of the far-field and near-field characteristics: radiation patterns, directivity, radiated power, and near-field patterns. This enables us to show that, to provide maximum directivity, the optimal edge illumination of the lens should be –8 dB, and the aperture feed should be spaced from the lens at small distance depending on the frequency.

Besides, to achieve a lens-like performance of layered cylinder, one needs no less than two layers, while taking more than 7 layers adds negligibly small to the directivity. These recommendations are valid in the broad band of frequencies. However, accurately computed frequency scans reveal periodic extremely sharp ripples produced by the WG resonances. If the number of layers is small, they can degrade the directivity of DA as much as by 10% even if the layers are lossless. This is because each m-th WG resonance radiates m equal beams to the far zone independently of the excitation.

Chapter 3 contains the analysis of the radiating properties of traveling wave rod-type DA, simulated with an elongated homogeneous dielectric cylinder of elliptic cross-section, excited by a CSP feed located inside the cylinder (Fig. 4). The analysis is performed by the elementary BIE method in combination with MAR. The brief outline of the method is as follows. Field functions are presented in terms of single-layer potentials over the scatterer contour S with the density functions to be determined:

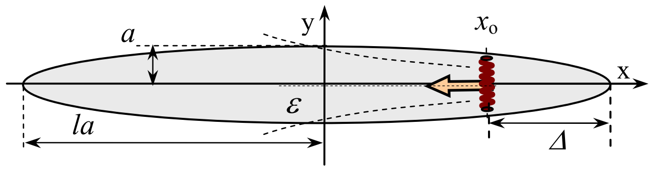

Fig. 4. Geometry and notations of a 2-D rod DA model

$$u_j(\vec r)=\int_S p_j(\vec r_s)G_j(\vec r,\vec r_s)dl_s\,, \qquad G_j(\vec r,\vec r_s)=\frac{i}{4}H_0\left(k_j|\vec r-\vec r_s|\right), \qquad j=1,2\,, \qquad (2)$$

Application of the boundary conditions and contour parameterization lead to a set of two logarithmic-singular BIEs of the Fredholm 1st kind ($L(t)$ is Jacobian of the contour S):

$$\begin{cases}\int_0^{2\pi} p_1(t_s)G_1(t,t_s)dt_s-\int_0^{2\pi} p_2(t_s)G_2(t,t_s)dt_s=u_0(t) & t,t_s\in[0,2\pi]\\ \dfrac{p_1(t)+\alpha_1 p_2(t)}{2\alpha_1}+\dfrac{L(t)}{\alpha_1}\int_0^{2\pi} p_1(t_s)\dfrac{\partial}{\partial n}G_1(t,t_s)dt_s-L(t)\int_0^{2\pi} p_2(t_s)\dfrac{\partial}{\partial n}G_2(t,t_s)dt_s=L(t)\dfrac{\partial}{\partial n}u_0(t)\end{cases}. \qquad (3)$$

By adding and subtracting, in the kernels, canonical-shape analogues, and by using a Galerkin scheme with angular exponents as global expansion functions, this set of elementary BIEs can be reduced to infinite matrix equation of the Fredholm 2nd kind:

$$\begin{cases} z_m^1 + \sum\limits_{m=-\infty}^{\infty} (A_{mn}^{11} z_m^1 + A_{mn}^{12} z_n^2) = B_m^1 \\ z_m^2 + \sum\limits_{m=-\infty}^{\infty} (A_{mn}^{12} z_n^1 + A_{mn}^{22} z_n^2) = B_m^2 \end{cases}, \qquad m = 0, \pm 1, \pm 2, \ldots \tag{4}$$

where $\{z_m^i\}_{m=-\infty}^{\infty}$ are unknowns to be determined, $\{A_{mn}^{ij}\}_{m,n=-\infty}^{\infty}$ and $\{B_m^i\}_{m=-\infty}^{\infty}$ $(i, j = 1,2)$ are essentially the expansion coefficients of the smooth functions in terms of double Fourier series. These matrix elements can be economically computed by using the DFFT algorithm. Such regularization plays the role of analytic preconditioning and guarantees point-wise convergence of the numerical solution (at any frequency except the defect ones), i.e. a possibility to minimize the error to machine precision by solving progressively greater matrices. The defect is common for all the elementary BIEs and restricts the applicability of all the numerical algorithms based on them.

In *Section 3.1*, the basic equations are derived, kernel properties of elementary BIEs (3) are studied, and analytical regularization is performed. This procedure is carried out by using the Galerkin discretization with angular exponents as global expansion functions leading to (4).

In *Section 3.2*, the mentioned above defect of the elementary BIEs is studied. The defect is related to the loss of uniqueness of the solution at some discrete real-valued frequencies, which are the discrete eigenvalues of the interior Dirichlet problem for *S*. In the realization of finite-order numerical algorithm this defect entails false resonances in the frequency-dependent field characteristics also called numerical resonances in the contrast to natural physical ones (Fig. 5).

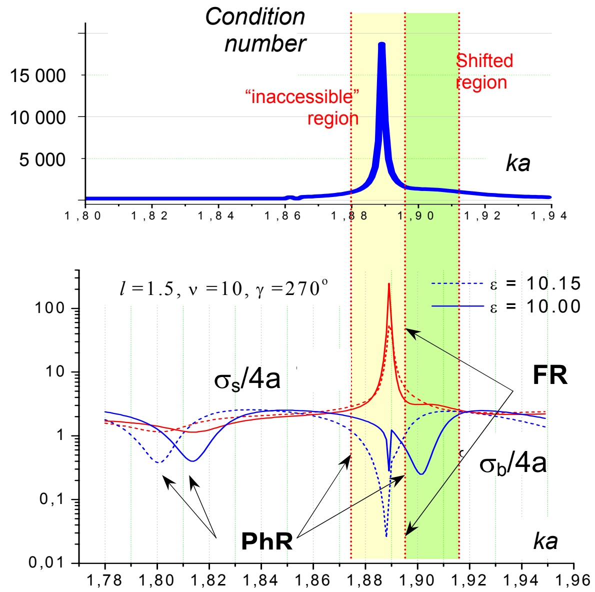

Fig. 5. Matrix condition number, and total and backward scattering cross-sections versus normalized frequency parameter ka.

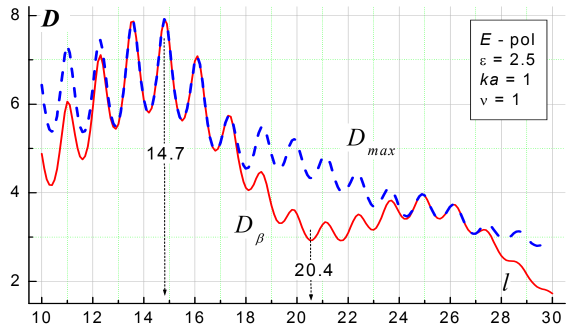

Fig. 6. Directivity versus the normalized rod-length parameter. Dashed and solid lines are for the directivity in the maximum lobe and along the axis, respectively. kb =0.1, β =180, kΔ=0.7, y_0 =0.

It is known that the spectrum of the defects gets denser at higher frequencies; and quality-factors of the false resonances depend on the accuracy of filling in the matrix and its order; the condition number of the corresponding discrete problem has poles at the defect points. It has been demonstrated that MAR does not eliminate the defect but enables one to narrow the "inaccessible" regions to very small values. Outside these regions the elementary BIE-MAR method has high efficiency in terms of accuracy and CPU requirements. A procedure enabling one to identify the false resonances and to perform interpolation of data into the "inaccessible" frequency intervals without losing the physical resonances is proposed. As false resonances correspond to eigenvalues of the interior problem for S, i.e. the eigenvalue problem for a perfectly conducting cavity with the same cross-section shape, their locations on the frequency axis are determined only by geometrical parameters and do not depend on the dielectric constant value. Thus change of ε results in a shift of the physical resonance along the frequency axis but does not effect on the false one (Fig. 5). Thus, there is no need for recalculation of all the data for a new value of ε. It is enough to repeat the calculation with increasing or decreasing argument (depending on the ε shift direction) near the false resonance, whose location corresponds to a “jump” in the condition number. After that, the interpolation of the field function into “inaccessible” interval is reduced to its replacement with the function obtained in the shifted region.

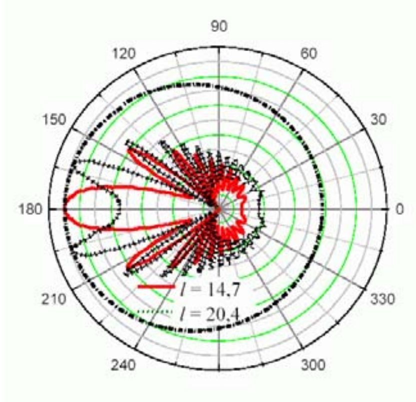

Fig. 7. Normalized radiation patterns corresponding to the maximum and minimum of directivity in Fig. 6. Dash-dotted line is for the pattern of the same CPS in the free space.

In *Section 3.3*, the numerical results for the aperture source directivity improvement due to elongated elliptical dielectric cylinder (Fig. 4), taken as a 2D model of a rod DA, are presented. The problem has been considered for the plane wave and beam-like field illuminations. The latter is taken as a beam of CSP located inside the cylinder. The solution is then obtained by the elementary BIE-MAR method. The analysis has been carried out in the frequency domain free of the defect values, that was verified by computing the matrix condition number.

The influence of the geometry and the size of the rod on the beam directivity have been studied. The importance of the proper choice of CSP location with respect to the rear end of the rod, and the rod length is shown. Sample far-field radiation patterns demonstrate the possibility of the directivity improvement as well as the main-lobe splitting for improper choice of parameters (Fig. 7). That makes invalid intuitive consideration "the longer rod, the better" and calls for a full-wave analysis.

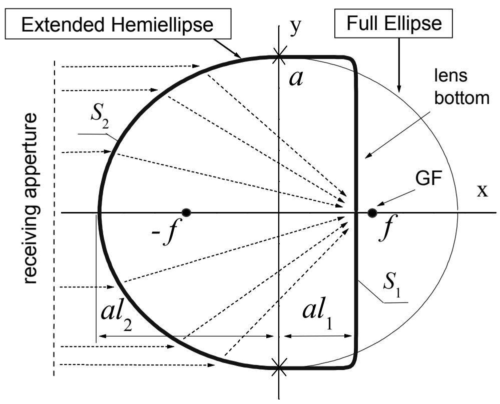

Fig. 8. Geometry and notations of an extended hemielliptical lens. The lens is characterized with a smooth junction of two curves S_1 and S_2 at the points marked with crosses. Dotted arrows are for the ray-tracing focusing diagram.

Chapter 4 presents accurate analysis of behavior of a 2-D model of an extended hemielliptic silicon lens for the plane *E*-wave illumination case. The lens is simulated by a dielectric cylinder whose contour is a smooth junction of an ellipse and a rectangle with rounded edges (Fig. 8). The full-wave analysis of the scattering problem is based on the Muller BIE technique. The method is based on the field functions representation in terms of a linear combination of single and double layer potentials over the scatterer contour:

$$u_j(\vec{r}) = \int_S \left[p_j(\vec{r}_s) \frac{\partial G_j(\vec{r},\vec{r}_s)}{\partial n_s} - q_j(\vec{r}_s) G_j(\vec{r},\vec{r}_s) \right] dl_s, \quad \vec{r} \in D_j, \quad \vec{r}_s \in S, \quad S = (S_1 \cup S_2), \quad j = 1,2 \qquad (5)$$

By applying the boundary conditions and contour parameterization, a set of the Fredholm 2nd kind BIEs is obtained, known as the Muller BIEs.

$$\begin{cases} p_1(t)-\int_0^{2\pi} p_1(t_s)A(t,t_s)\,dt_s+\int_0^{2\pi} q_1(t_s)B(t,t_s)dt_s=L(t)\,u_0(t) \\ \left(1+\frac{\alpha_1}{\alpha_2}\right)\frac{q_1(t)}{2}-\int_0^{2\pi} p_1(t_s)C(t,t_s)\,dt_s+\int_0^{2\pi} q_1(t_s)D(t,t_s)dt_s=L(t)\frac{\partial u_0(t)}{\partial n} \end{cases} \quad t,t_s\in[0,2\pi] \qquad (6)$$

Further we discretize (6) by applying the Galerkin method with entire-domain angular exponents as expansion functions. To treat the (integrable) singularities in some of the kernel functions, we use analytical integration of the canonical circular-cylinder counterpart terms. This procedure results in a Fredholm 2nd kind infinite-matrix equation having favorable features, with matrix elements and right-hand-part terms obtained as Fourier-expansion coefficients of some twice-continuous functions. They can be economically computed by using the DFFT and FFT algorithms, respectively. The obtained matrix equation structure is similar to (4), but unlike that one (obtained by the elementary BIE method), it has unique solution for an arbitrary set of lens parameters e.g., frequency and contrast between the lens material and the background medium. This makes the Muller BIE method the most reliable tool for a cylindrical DA analysis.

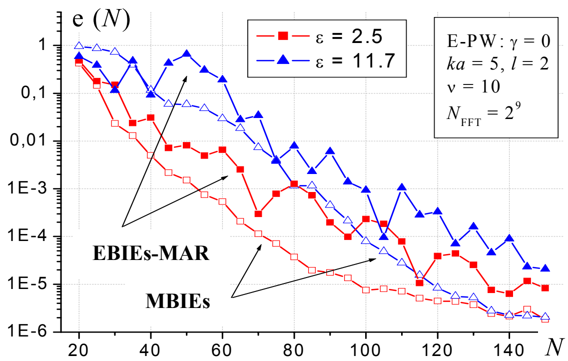

Fig. 9. Comparison of the relative errors for the numerical algorithms based on the elementary and the Muller BIEs versus the matrix truncation number.

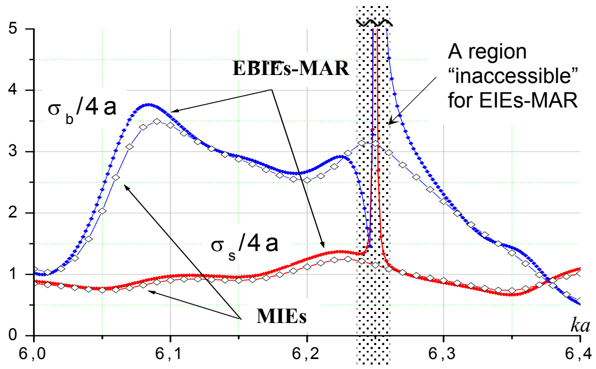

Fig. 10. Total and backward scattering cross-sections calculated by the elementary and Muller BIEs methods versus the normalized frequency parameter near a defect point.

In *Section 4.1*, the basic equations of the method are derived; kernel properties of the Muller BIEs (6) are studied; analytical integration of the canonical circular-cylinder counterpart terms is performed. Further, a BIEs discretization based on the Galerkin scheme with angular exponents as global basis functions is done that leads to an infinite matrix equation of the Fredholm 2nd kind.

In *Section 4.2*, a comparison of the numerical algorithms based on elementary BIEs-MAR and the Muller BIEs is performed. It is proved that the algorithm based on the Muller BIEs has somewhat better convergence (Fig. 9) and provides accurate simulation for all parameter values including those corresponding to defects of the elementary BIEs (Fig. 10).

In *Section 4.3*, electromagnetic behavior of an extended hemielliptical (EHE) and semicircular (ESC) lenses are studied for the plane *E*-wave incidence. ESC lens is the simplified case of EHE lens with $l_2 = 1$, and commonly used in practical applications. A comparison of their performance and a search for optimal geometrical parameters are fulfilled.

The ability of the lens to focus the radiation along the *x*- and *y*-axes can be quantified by the "focusability" defined as a ratio of the highest field intensity inside the lens to the width (along the corresponding axis) of the focal domain at the level of the half maximum intensity value.

Fig. 11 shows the focusability of the EHE and ESC lenses versus the flat bottom extension parameter, l_1. Here, instead of a stable value suggested by GO approximation, the resonance effects are well seen. Comparison of the graphs for EHE and ESC lenses demonstrates a better EHE lens focusing ability and a shift of the resonant values of l_1 for the ESC lens, while in general both lenses behave in similar manner.

The evolution of the point with the highest field intensity inside the lens along the x-axis versus the extension parameter l_1 is shown in Fig. 12. It is seen that for both types of the lenses this point is located inside the lens for any value of l_1. Moreover, it moves between the full ellipse geometrical focus location and the lens bottom, and its exact location is complicated function of l_1.

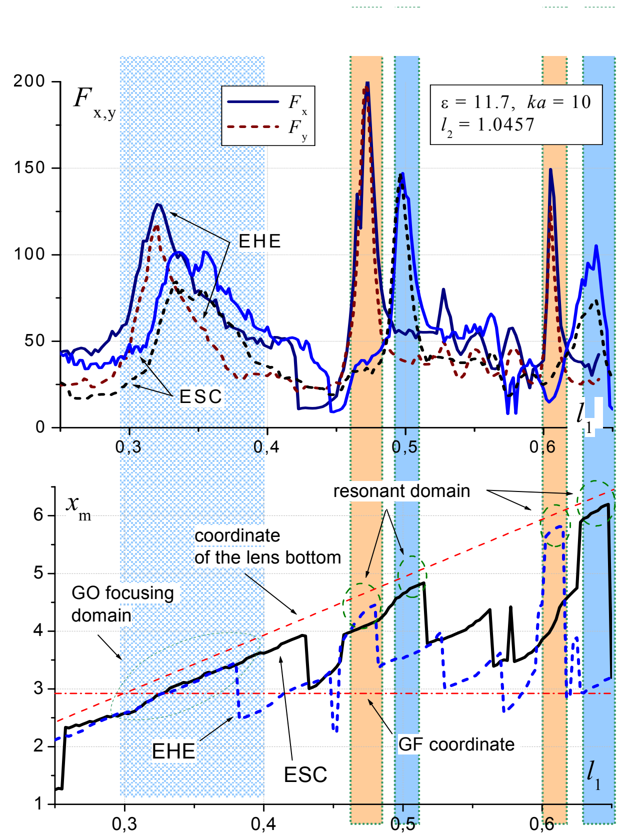

Fig. 11. Focusability versus the lens extension parameter for the EHE and ESC lenses.

Fig. 12. Evolution of the point with the highest field intensity along the x-axis versus the same lens extension parameter for both types of the lenses.

Joint analysis of the graphs shows that if the lenses are extended up to a distance shorter than the GO focal distance ($l_1 \approx 0.3$), than the focal domains are shifted inside the lenses, keeping stable their locations with respect to the lens bottoms. An increase of the extension parameter up to the values of 0.32 and 0.35, for EHE and ESC lenses, respectively, results in a continued growth of the focusability - up to more than 200% in comparison to the focusability of the lens extended up to the geometrical focus, and also in a rise in the peak field intensity.

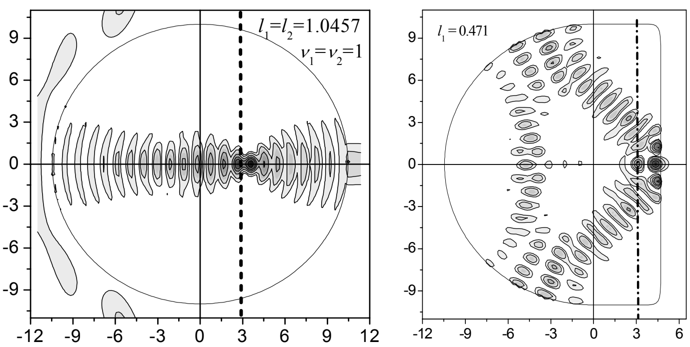

Fig. 12. Near-field intensity portrait for the EHE lens with bottom extension parameter corresponding to the geometrical focus locations and to the first resonance.

A further increase of the bottom extension is accompanied by even more complicated behavior of the focal domain. In Fig. 12, it is seen that despite the increased part of the lens behind the rear geometrical focus, the field concentrates somewhere around the focus until the resonance conditions are satisfied. Internal resonance results in a large concentration of the field at the bottom of the lens and in a more then three-time growth of focusability. Further extension reveals a sequence of resonances.

The near-filed intensity portraits for a full elliptic lens (not cut at all) and an EHE lens with l_1 corresponding to the first resonance seen in Fig. 10 are shown in Fig. 12. It is visible that the truncation of elliptic shape leads to tremendous change in the field pattern inside the lens.

The resonance pattern resembles, to some extent, asymptotic GO resonance sometimes called “billiard-type” one. Here it has specific triangular portrait and can be characterized with two indices, which are for the variations of the field along the lens flat side (m) and the side of “triangle” (n). Two neighboring resonances in l_1 have n and $n+1$ variations, respectively, and the distance between them corresponds to half a wavelength in dielectric along the “triangle” side.

Analysis shows that EHE lens tuned to an internal resonance has certain advanced properties, namely stability of the resonance field with respect to the angle of arrival of incident wave and several times greater value of the peak intensity. Narrow-band multi-detector receiver exploiting this effect may potentially show an improved sensitivity and scanning performance. Thus, the most important feature revealed by the accurate analysis is that the resonances play a dominant role in the wavelength-scale lens behavior.

CONCLUSIONS

1. The problems of the electromagnetic field radiation and focusing by cylindrical DAs have been systematically considered as boundary-value problems for the Maxwell equations in the open domains.

2. As an advanced and more adequate model of directive incident field emitted by a flat-aperture source, the CSP beam field has been systematically used.

3. In the problems of scattering by smooth homogeneous cylinders, a defect of the elementary BIEs has been demonstrated; it has been shown that even the analytical regularization does not eliminate this defect, caused by the loss of uniqueness of the solution at some discrete real-valued frequencies.

4. An effective numerical algorithm for uniquely solvable Muller BIEs based on the trigonometric-Galerkin discretization scheme has been developed.

5. Radiation characteristics of DA based on a discrete cylindrical Luneburg lens have been studied in accurate manner; it has been demonstrated that the number of layers of such a lens should be between 2 and 7, and the optimal edge illumination is -8 dB.

6. Electromagnetic wave radiation by a thing rod-like DA excited by a CSP located inside the rod has been studied; it has been shown that optimal rod length is a complicated function of the wavelength and dielectric constant; intuitive consideration "the longer rod, the better" is invalid; improper choice of the rod parameter may result in the main lobe splitting.

7. Focusing properties of lens DAs of most practical geometries, namely, elliptical, extended hemielliptical and semicircular ones, have been studied; it has been demonstrated that resonant effects play dominant role in the wavelength-scale lens behavior; shape, size and location of the focal domains or domains of peak intensity are complicated functions of the wavelength, dielectric constant and the angle of the plane wave incidence.

8. Based on the analysis, a design of EHE lens tuned to internal resonance and having promising characteristics has been proposed.

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3. A.V. Boriskin, 'Advanced numerical simulation of a 2-D elliptic dielectric lens used to improve the directionality of an aperture source', *Radio Physics and Electronics*, Kharkov: IRE Press, 2002, vol. 7 Special Issue, pp. 254-258, (in Russian).
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