KHARKOV STATE UNIVERSITY

Radio Physics Department

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The scattering of surface waves and beams by open-waveguide discontinuities and by reflectors

Summary

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The study has been done at the Chair of Theoretical Radio Physics of the Kharkov State University

Key words: dielectric resonator, whispering-gallery-modes, metal cavity resonator, bandstop filter, directional coupler, losses, cylindrical reflector, complex source, imperfect earth, analytical regularization.

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English version of the thesis is available upon request.

Research problems. In the dissertation, we study the two-dimensional (2-D) problems of electromagnetic wave scattering from the localized dielectric and metal scatterers placed in a flat-layered dielectric medium backed by a ground plane. Similar problems are frequently encountered in various areas of applied science: microwave technologies, communications, geophysics, hydroacoustics, etc. We shall be interested in the radio physical applications. Therefore the scope of considered research problems will encompass: 1) full-wave analysis of several open-waveguide functional components such as filters and couplers, and also 2) analysis of reflector antennas near an interface. More specifically, the problems are as follows:

(a) the scattering of a surface-wave guided mode of a slab waveguide from a circular dielectric cylinder as a model of the whispering-gallery-mode (WGM) bandstop filter,
(b) the same as above but for a dielectric tubular cylinder as a modified filter,
(c) the scattering of a complex-source-point (CSP) beam from a circular dielectric cylinder as a model of WGM directional coupler,
(d) the scattering of a surface-wave mode from a metallic circular-cylindrical slitted cavity as a model of a resonant rejection filter,
(e) the scattering of CSP beam from a metallic circular-cylindrical reflector near a flat impedance boundary, as a realistic model of a reflector antenna near imperfect flat earth,
(f) the scattering of waves dielectric cylinders of arbitrary smooth cross-section shapes.

Scientific significance of the study follows from the fact that the simulated devices are widely used in today microwave, millimeter-wave and optical technologies. However, existing simulation tools are still based on approximate theories having unclear and uncontrollable accuracy and not taking a full account of all the interactions between different parts of localized scattering objects and infinite boundaries. This prevents one from studying the physics of the wave phenomena in accurate and reliable manner, and from using approximate methods as a basis of computer-aided design (CAD) tools. Hence, it is significant to develop convergent, reliable and economic algorithms based on the mathematically accurate treatment of the corresponding boundary-value problems for the Maxwell equations in layered media. To this end, the treatment should use the specific concept of analytical regularization, which guarantees the convergence of discretized numerical solutions.

Timeliness of research.

Dielectric and metal cylindrical scatterers in a slab waveguide. Localized discontinuities in open waveguides (OW) are known as important components of many optical and millimeter wave electronic systems that are based on the surface wave propagation. They are used as elements of integrated couplers, leaky-wave antennas, filters, resonators, etc. Design and manufacturing of such devices is a complicated technical task. To reduce their cost and improve the electromagnetic performance, a preceding CAD simulation, by using a reliable method and a moderate computer hardware, is highly desirable. So far, simulations of relevant metal and dielectric discontinuities have been based mainly on approximate theories summarized in[1]. Further theoretical and experimental work is necessary to reveal the potentials and optimize the performance of the OW couplers, filters, and other passive devices. Far field radiation patterns, guided mode amplitudes, and overall efficiencies are at best estimated rather than calculated, thus calling for a development of novel approaches. A more accurate analysis is especially important if studying the millimeter-wave applications, instead of optical ones, because here the device dimensions are comparable to the wavelength. It was only recently that adequate mathematical methods have been proposed, enabling one to attack the problem in correct full-wave manner[2]. However, these works did not study specific applications such as filtering and coupling in OW.

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[1] R.G. Hunsperger, Integrated Optics. Theory and Technology, Berlin, Springer-Verlag, 1995.
[2] V.I. Kalinichev, P.N. Vadov, “A Numerical Investigation of the Excitation of a Dielectric Resonator”, *Soviet J. Commun. Technol. Electronics (English Transl.)*, 1998, vol. 33, no. 7, pp. 108-115.
A.G. Yarovoy, “Scattering from an Internal Penetrable Inhomogeneity of a Dielectric Slab Waveguide”, *Microwave Optic. Technol. Lett.*, 1994, vol. 7, no. 4, pp. 178-182.

Cylindrical reflector antenna near an imperfect earth. Reflector antennas (RA) are known as major components of many ground-based and spaceborn radio frequency systems. They are used in satellite communications, anti-collision, aiming and surveillance radars, radio astronomy, vehicle tracking, etc. Increasing demands for improved electrical performance of RA have stimulated a significant progress in the application of CAD tools for their analysis and optimization. Wherever possible, a theoretical model involving advanced mathematical and computational techniques should be developed to provide predictions of radiated electromagnetic fields of antennas.

Any RA consists of at least one primary feed and one reflector. To reduce the effect of finite-size aperture (i.e., spillover, edge diffraction, etc.), the feed is always a directive source providing a reasonably small edge illumination. However, so far the feed simulations have been based on the Gaussian beam or angular-tapered cylindrical/spherical wave representations. In spite of simplicity, one important shortcoming of such functions is that they are not solutions of the full wave equation. Hence, they loose the accuracy of the field approximation out of certain space domain.

In the modeling of the scattering from reflector, so far the most widely used theoretical approach has been the Physical Optics (PO). Most of existing CAD software tools are based on PO, sometimes combined with the Geometrical Theory of Diffraction (GTD). However, both PO and GTD have some instrinic limitations due to their asymptotic high-frequency nature. PO predicts well the main beam but yields no reliable data on the spillover and rearside radiation. In the contrast, GTD fails for the main beam but is able to predict the far sidelobes. Further, PO and GTD are inaccurate for calculating smaller reflectors comparable to the wavelength, and RA in the complicated near-zone environments characterized by a strong interaction of various scatterers. In this case, the Method of Moments (MoM) can be used that is based on numerical approximation of the rigorous electric-field integral equations. However, this is a time and memory consuming approach that limits calculatable reflectors to small aperture size if a moderate computer is used. Besides, MoM convergence is not uniformly guaranteed and actually depends on implementation. Thus, it is interesting to have a uniformly reliable tool of RA radiation pattern prediction, especially if additional scatterers are present in the near zone, and especially in the gap between MoM and PO.

Many of the mentioned shortcomings in the analysis of OW discontinuities and RA’s can be overcome if one uses the concept of analytical regularization. This implies a rigorous conversion of the singular integral equations to the Fredholm second-kind equations, either integral or infinite-matrix ones. This guarantees the convergence and accuracy of computations. For cylindrical reflectors, such an approach has been developed in[3]. Later it was applied to reflectors with an edge loading[4] and in a radome[5]. Our present study of cylindrical RA near a flat imperfect earth is in line with the further development of the mentioned analysis.

Relation to R&D projects and programs. This study has been done at the Chair of Theoretical Radiophysics of the Kharkov State University in line with the research program "Prospective information technologies, devices of integrated automation of systems of communication". It was also in the framework of the following research projects:

- "Reflector Antennas Analysis and Modeling" (1995-96), *TUBITAK-DOPROG*, jointly with Bilkent University, Ankara, Turkey.
- "Development of novel analytical-numerical approaches to wave scattering by dielectric and metal bodies in slab waveguides, and by reflector antennas in layered medium" (1996), Graduate Fellowship in Advanced Electromagnetics, *SUMMA Foundation*, USA.
- "CAD-oriented numerical analysis of surface-wave filters and couplers" (1997), Microwave Engineering Graduate Scholarship, *IEEE Microwave Theory and Techniques Society*.

[3] T. Oguzer, A. Altintas, A.I. Nosich, “Accurate Simulation of Reflector Antennas by the Complex Source-Dual Series Approach”, *IEEE Trans. Antennas. Propagat.*, 1995, vol. 43, no. 8, pp. 793-801.
[4] A.I. Nosich, V.B. Yurchenko, A. Altintas, “Numerically Exact Analysis of a 2-D Variable-Resistivity Reflector Fed by a CSP”, *IEEE Trans. Antennas Propagat.* , 1997, vol. 45, no. 11, pp. 1592-1601.
[5] V.B. Yurchenko, A. Altintas, A.I. Nosich, “Numerical Optimization of a Cylindrical Reflector-in-Radome Antenna System”, *IEEE Trans. Antennas Propagat.*, 1999, vol.47, no. 4.

The aims of this study are:
1. Develop numerically accurate, i.e., convergent and economic, algorithms for modeling the listed problems, based on the concept of analytical regularization.
2. By using these algorithms, perform physical analysis of the wave fields and overall characteristics of the simulated devices.

In the study of open-waveguide components, our specific aims are to:
- clarify the role of the radiation and absorption losses in the WGM filter performance,
- study the effect of the higher-order guided modes on the WGM filter,
- study the merits of a tubular WGM filter,
- compare two alternative polarization cases of WGM filters,
- verify the potentialities of a WGM directional beam coupler,
- show the features of a resonant rejection filter based on metallic circular cylindrical slitted cavity,
- generalize the approach towards studying arbitrary-shape dielectric scatterers,

In the study of reflector antennas, our specific aim is to:
- study the effect of an imperfect flat earth on the directivity, gain, and sidelobe level of RA's.

Method of research. To achieve the objectives, we have used advanced mathematical methods of electromagnetic theory of wave scattering. The first is the Green's function method which implies that the full Green's function (E or H-type) of a host medium (halfspace bounded by a conductor-backed dielectric slab or impedance plane) is obtained analytically, and further used to derive the integral equation (IE) governing the field. Hence, satisfying the slab-interface continuity conditions is guaranteed, as well as accounting of all guided and leaky modes of the OW. The second is the family of techniques, which is collectively called the Method of Analytical Regularization (MAR)[6], to treat the wave scattering problems in mathematically accurate manner. It starts from a singular IE obtained from the boundary conditions. Unlike with MoM, further it is partially inverted analytically, that results in the infinite matrix equation of the Fredholm 2-nd kind, thus giving a proof of existence of unique solution. This procedure is equivalent to a judicious choice of basis/testing functions in MoM that form a set of orthogonal eigenfunctions of the inverted part of IE. Numerical solution of such a matrix equation is always stable and efficient in terms of memory and CPU time expenditures.

To analyze optical waveguide beam couplers and reflector antennas, it is supposed to use the Complex Source Point (CSP) field as a specific excitation function, to simulate a beam-like incident wave. Indeed, by adding an imaginary part to a point (or line) source location in the real space, one obtains a directive radiation pattern. In the far zone it posseses the features of the Gaussian beam, but what is more important, it is still an exact solution of a full wave equation at any point of space.

To study the localized dielectric discontinuities, we use the surface potential method, extracting out and analytically inverting the free-space-circular-cylinder part of IE. To analyze a metallic curved-strip scatterer, the static part of the electric field IE is inverted.

The novelty of research is determined by the following original results that are obtained for the first time:
- WG-mode filters are essentially the dissipation filters, where the stopband feature is achieved due to combined effect of the radiation and absorption losses,
- excitation of a higher-order surface-wave guided mode results in the abrupt increase of the mode conversion coefficients, accompanied by the decrease of the losses in a WGM filter,
- tubular-cylindrical design of a WGM filter enables one to rarefy the spectrum of a dielectric resonator by eliminating the parasitic oscillations having multiple field variations along the radius,
- the H-polarization WGM filter has an advantage before the E-polarization one, in a less pronounced effect of parasitic oscillations and higher Q-factors of working ones,

[6] A.I. Nosich, "The Method of Analytical Regularization in Wave Scattering and Eigenvalue Problems", *IEEE Antennas Propagat. Magazine*, 1999, vol.42, no.2.

- WGM directional coupler is able to convert at least 50% of the source beam power into a contra-directional surface wave;
- a filter based on a slitted metal cavity is able to reject the incident surface wave instead of dissipating its power; in the H-polarization case, a low-frequency resonance filter is promising,
- CSP beam has been used to simulate a directional excitation of the WGM couplers and reflector antennas,
- the effect of imperfect flat earth on the radiation pattern, including the sidelobes, directivity and gain of reflector antenna has been studied,
- all the above results have been computed with a uniform relative accuracy of 10^{-4}; however, the developed algorithms enable one to minimize the error to 10^{-14} by solving the larger matrices,
- the method of analytical regularization has been developed to study the scattering from arbitrary-shaped dielectric cylinders in layered medium; the properties of the method have been studied and its application to simulate prism couplers and rectangular resonators have been discussed.

Practical impact. Dielectric and metal discontinuities are used in various optoelectronic surface-wave devices and networks. Similar concepts are applied in microwave and especially millimeter wave bands. A more accurate and uniform data on the electromagnetic behavior can obviously contribute a great deal to better understanding and hence better performance of such systems. Within the full-wave formulation, it is possible to make a rigorous comparison, in terms of efficiency, between different types of WGM couplers, resonators, rejection and bandstop filters. Worth noting is that similar concepts and results (sometimes, completely the same ones) are valid in the scattering and conversion of acoustic waves, with applications in hydroacoustics. RA's are used in the numerous ground and sea-based systems for communication, tracking, guidance and aiming, in the microwave and millimeter wave bands. More reliable and informative data on the electromagnetic behavior of RA in the presence of material interface can lead to the development of antennas having improved performance.

Efficiency, in terms of CPU time and memory, of the numerical algorithms, which exploit the analytical regularization, is very high. Furthermore, they are uniformly accurate both near and far from the resonances. All this enables one to use them as a basis of the new generation software tools of CAD of the surface-wave circuits and reflector antennas.

Author's personal contribution is proven by a number of the journal and conference papers, which have been published and accepted for publication in 1995-1998.

In the works [1-6,8-16] the author took part in the development of the theoretical approach, obtaining the basic equations, and discussion of the numerical results.

In the works [1-16] the author developed efficient computer codes, performed all the numerical calculations, and interpreted the results of analysis.

Presentation of results. Obtained results have been presented and discussed at the following meetings: International Conferences on Mathematical Methods in Electromagnetic Theory, Kharkov, Ukraine, 1998, Lviv, Ukraine, 1996; IEEE AP-S & URSI International Symposium, Baltimore, USA, 1996; NRSC & QMW Antenna Symposium, London, UK, 1995; MIKON International Conferences, Warsaw, Poland, 1996, Krakow, Poland, 1998; 22nd International Symposium on Infrared and Millimeter Waves, Wintergreen, USA, 1997; Colloquium on Hertzian Optics and Dielectrics, Clermont-Ferrand, France, 1997; Progress in EM Research Symposium, Nantes, France, 1998; International Workshop on Optical Waveguide Theory and Numerical Modeling, Hagen, Germany, 1998; European Microwave Conference, Amsterdam, the Netherlands, 1998; Asia-Pacific Microwave Conference, Yokohama, Japan, 1998; International Symposium on Antennas, Nice, France, 1998.

Publications. Based on the obtained results, five journal papers have been published and another one accepted for publication; also, 10 conference papers have been published.

Organization of the dissertation. The thesis consists of the introduction, literature review, three original chapters, conclusions, and references including 1xx items. The outline of the thesis is as follows.

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

Chapter 1 presents a review of the state-of-the-art of modeling of electromagnetic wave scattering from localized objects. Commonly used IE approaches to the solution of these problems are discussed and compared. The role and the merits of analytical regularization are explained.

Chapter 2 is devoted to the modeling of WGM bandstop filters (Fig. 1) and directional beam couplers (Fig. 5) based on the circular cylindrical and tubular DR's. The scattering problem for the total field U, which represents either E_z or H_z component, can be reduced to a set of the coupled boundary IE's by using the surface-potential approach. Here, the kernels of IE's are the E-(H-) type Green's function of the homogeneous medium with permittivity ε_b, and the Green's function of the halfspace bounded by a grounded dielectric slab; and their normal derivatives. In the case of a solid circular cylinder only one pair of the IE's takes place, while for a tubular cylinder two pairs of IE's are derived.

The functions $\left\{e^{in\varphi}\right\}_{n=-\infty}^{\infty}$ form the set of orthogonal eigenfunctions of all the integral operators of derived IE's if the Green's function of the slab waveguide is replaced by its free-space counterpart. By using this set as expansion functions in the Galerkin-type discretization scheme, we can perform a partial analytical inversion, i.e., a regularization of our IE's. This procedure involves an inversion of the frequency-dependent part corresponding to a free-space circular cylinder. On using some algebra and the orthogonality of exponents in the term-by-term integrations, arrive at the Fredholm second-kind infinite-matrix equation for the field expansion coefficients.

Numerical solution of the resulting matrix equation allows obtaining the total field value in every point of space. In the far zone of the scatterer this field is to satisfy a modified radiation condition and can be presented as follows:

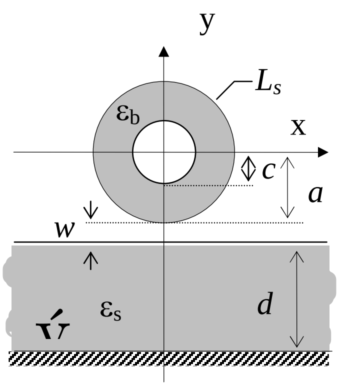

Fig. 1. WG-mode dielectric filter in a dielectric slab waveguide

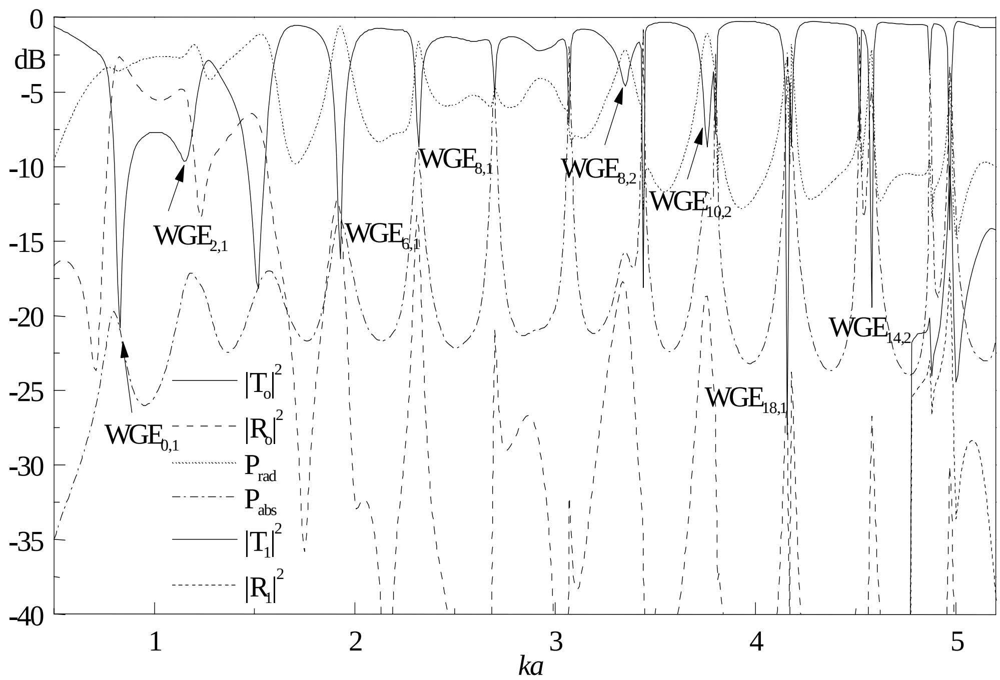

Fig. 2. Far-field scattering characteristics versus ka for the scattering from a circular cylindrical DR. (ε_b=10+0.01i, w/a=0.01, d/a=0.6, ε_s=2.25, $w=b-a$)

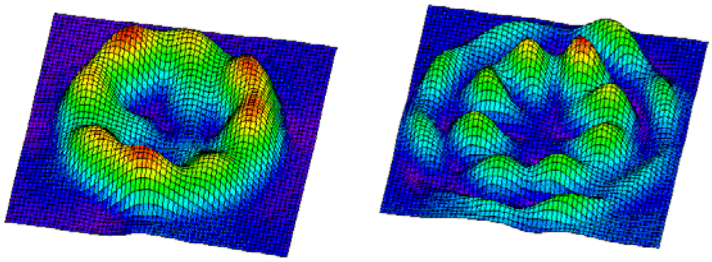

Fig. 3. The H-field spatial portraits at the resonances $WGE_{6,1}$ (left) and $WGE_{8,2}$ (right)

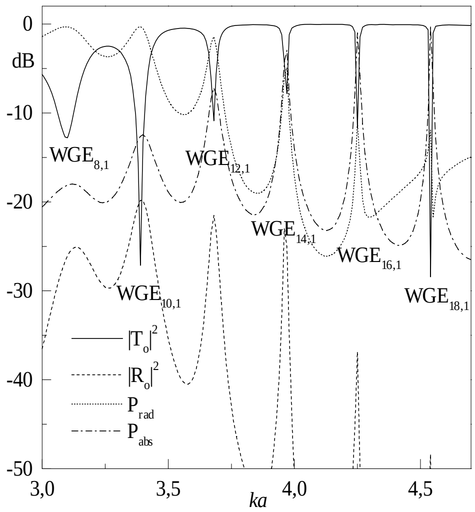

Fig. 4. Filter characteristics versus *ka* for the tubular dielectric resonator.
$c/a = 0.7,\ \varepsilon_b = 10 + 0.01i,$
$d/a = 0.6, \varepsilon_s = 2.25, w/a = 0.01$

$$U^{sc}(\vec{r}) \underset{r\to\infty}{\approx} \sqrt{\frac{2}{i\pi kr}} e^{ikr} \begin{Bmatrix} \Phi^{E(H)}(\varphi), & y > -b \\ 0, & -(b+d) < y < -b \end{Bmatrix} + \sum_{n=1(0)}^{Q^{E(H)}} \begin{Bmatrix} T_n^{E(H)} - \delta_{ns}, & x > 0 \\ R_n^{E(H)}, & x < 0 \end{Bmatrix} V_n^{E(H)}(y) e^{ih_n|x|}$$

Here, δ_{ns} is the Kronecker delta, s is the index of the incident guided wave, $1(0)\leq s\leq Q^{E(H)}$, where $Q^{E(H)}$ is the total number of the higher-order guided modes supported by the slab at the given frequency; $\Phi^{E(H)}(\varphi)$ is the far-field radiation pattern, $T_n^{E(H)}$ and $R_n^{E(H)}$ are the mode conversion coefficients. Sample numerical results for the mode-conversion coefficients, radiated (P_{rad}) and absorbed in the resonator (P_{abs}) power fractions, and discussion of the filter and coupler performance are presented. To study the filter characteristics of DR, we consider a dielectric waveguide surface mode as an incident field. Sharp resonant phenomena are observed in the scattering of guided modes from a circular solid dielectric cylinder (see Fig. 2 as an example). One can see that DR's can be used as the bandstop filters in the surface-mode waveguides. The principle of operation of such filters is based on the excitation of the WG modes ($WGE(H)_{m,n}$-modes depending on the polarization) in the resonator. The first subscript *m* denotes the number of the azimuthal field variations, the second *n* denotes the number of the radial variations (Fig.3).

It is demonstrated that the analyzed filters are dissipation filters rather than rejection ones, whatever small the loss tangent is of the material used. It is shown that removing the dielectric material from the central part of the resonator does not effect the $WGE(H)_{m,1}$ resonances, unless the inner radius of the ring approaches the caustic, but eliminates parasitic resonances (Fig.4). It has been also revealed that at the birth of a new surface mode all the power characteristics experience an abrupt change.

To study the coupling of an outer beam field into an open waveguide through a dielectric coupler, we use the CSP concept to obtain the incident beam field. It means that we consider a line feed with the complex source coordinates. Thus the complex source position vector is: $\vec{r}_{cs} = \vec{r}_0 + ib(\vec{e}_x \cos\beta + \vec{e}_y \sin\beta)$. Here the real value *b* is a measure of the beam width, and the angle β counted from the *x*-axis represents the beam direction. Such a feed produces a beam-like field in the real space. This field is an exact solution of the Helmholtz equation at any observation point, unlike the Gaussian-type exponents frequently used to approximate the beam fields in paraxial domains. Note that the power carried by a CSP field has a finite value, in contrast to the plane-wave power.

One of the principal characteristics of a coupler is its efficiency, which is defined as the ratio of the right (left) moving guided mode power excited in the waveguide to the incident beam power. Performed numerical calculations show that a selective WGM coupler is essentially a contra-directional one. WG mode field is matched with the surface-wave field propagating in the opposite direction relatively to the incident beam propagation. It has also been shown that a WGM directional coupler is able to convert at least 50% of the source beam power into a single contra-directional surface wave or two oppositely moving surface waves (Fig. 6).

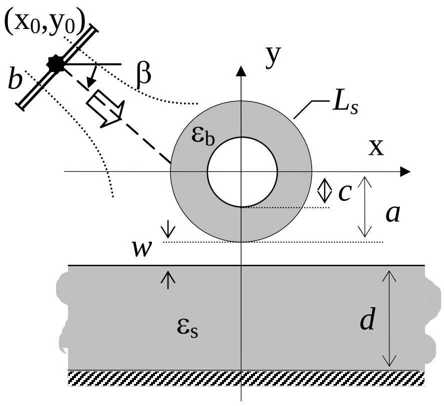

Fig. 5. WG-mode directional coupler in a dielectric slab waveguide

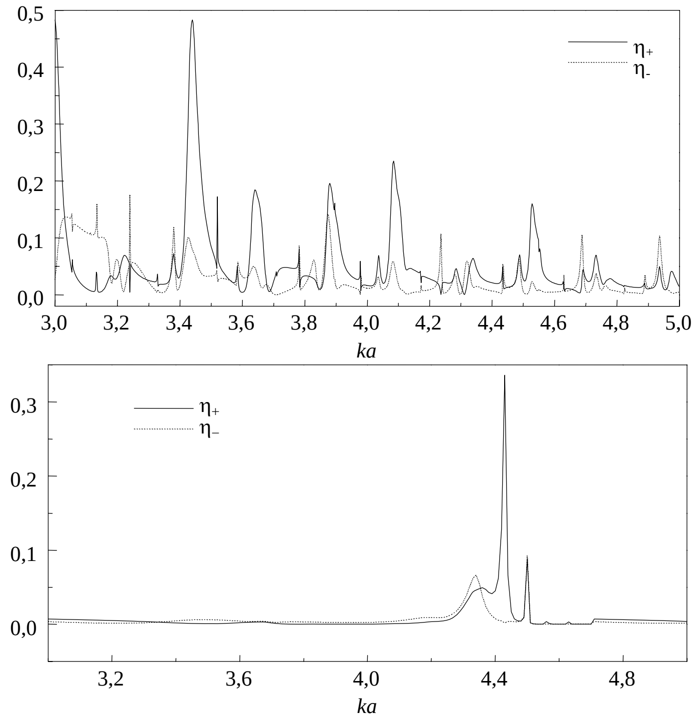

Fig.6. Right (left) moving guided wave coupling efficiencies ($\eta_{\pm}$), H-polarization. *kb*=0.5, y_o/a=1, x_o/a=1, ε_b=50, ε_s=2.25, β=180^o, *w/a*=0.01, *d/a*=0.6; a) *c/a*=0, b) *c/a*=0.7

Chapter 3 is devoted to the modeling of the performance of a metal slitted circular cavity resonator in a dielectric slab waveguide and a cylindrical reflector antenna in the vicinity of imperfect flat earth. A circular PEC screen of the radius *a* is elevated at the height *c* over a reflecting surface; its angular width is $2\theta_{ap}$, $\theta_{ap} = \pi - \theta$, and inclination angle with respect to the *x*-axis is φ_O (Figs.7,9). We consider the case of the H-polarized incident field. Therefore the electromagnetic boundary value problem can be formulated for the single component of magnetic field, H_z.

By representing the scattered field in the form of a double-layer potential and imposing the boundary conditions we obtain a hyper-singular IE. Here the unknown function is the surface current density induced on the screen by the incident field. The kernel depends on the "magnetic" Green's function of the halfspace bounded by a reflecting surface. Equations of this type can be solved numerically by a direct application of MoM. However, the solution scheme based on the analytical inversion of the static part of IE is much more efficient.

The current density function is completed with identical zero on the slot, and further discretized

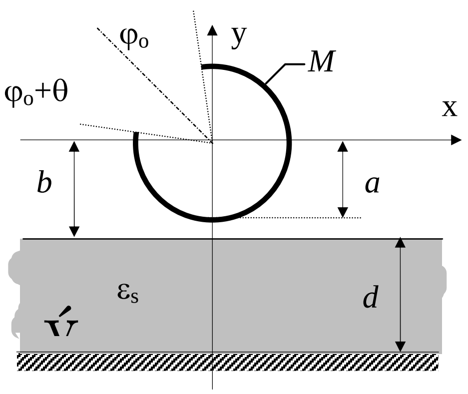

Fig. 7. Slitted cavity rejection filter in a dielectric slab waveguide

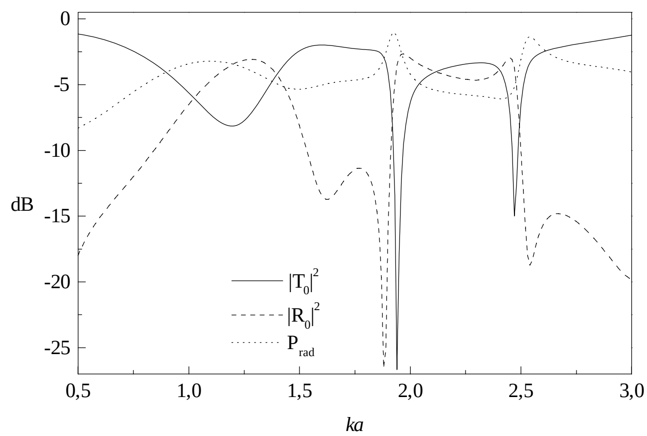

Fig. 8. Far-field characteristics for the scattering from a slitted cavity resonator:
$w/a = 0.01, \varphi_0 = 270^o, \theta = 40^o, d/a = 0.5, \varepsilon_s = 1.3$

in terms of angular exponents. Term-by-term integration and differentiation in IE, together with separation of the static and dynamic parts leads to the dual series equations in canonic form for the current expansion coefficients. Further we invert analytically the static part of the free-space term of the series equations that brings us to the infinite Fredholm second-kind matrix equation.

Consider an *H*-polarized guided mode of the grounded dielectric layer incident from the left on a circular slitted metal cylinder (Fig. 7). Computations show that a slitted metal cavity offers a way to avoid the excessive radiation and minimize the electric size of the filter. In Fig. 8, the typical frequency dependences of transmitted, reflected, and scattered power fractions for the scattering from a metal slitted cavity are shown. If excited by the surface wave field, the cavity gives a resonant response provided that the frequency coincides with the real part of a complex natural frequency of the slitted cavity. In general, these eigenfrequencies are related to several families of modes. It can be observed that antisymmetric cavity resonances have a larger Q-factor then symmetric ones. The first low-frequency resonance is due to the symmetric Helmholtz mode of a cavity-backed aperture, perturbed by the presence of the slab. The Helmholtz mode frequency is a complex number tending to zero when $\theta \to 0$. So, by narrowing the slot, one can obtain a miniature low-frequency rejection filter with a remarkably low parasitic radiation: more than 90% of the incident mode power can be converted to the reflected guided mode. We did not consider the case of *E*-polarization because the most interesting low-frequency resonance does not exist in this case.

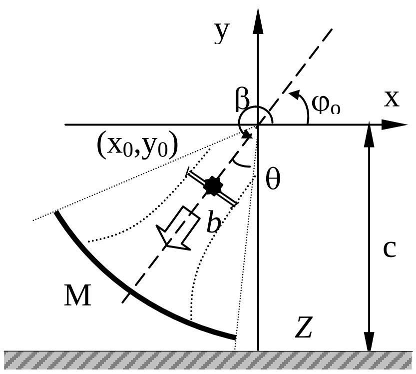

Fig. 9. 2-D RA geometry.

A circularly curved metallic strip can also serve as a model of cylindrical reflector (Fig.9). Zero-thickness PEC reflector is located in the air above the plane surface with impedance $Z_o Z$, where Z_o is the free-space impedance. Reflector cross-section *M* is assumed a circular arc of radius *a* elevated at the height *c*; its angular width is $2\theta_{ap}$ and inclination angle with respect to the *x*-axis is φ_o. Although practical reflectors are of parabolic shape, they can be well approximated by circular ones if the focal distance of the parabolic arc *F* is large enough with respect to the reflector aperture *L*.

We simulate the directive radiation of a primary 2-D feed by using the CSP method. This enables us to include the effect of variable edge illumination in the accurate analysis.

The far-field radiation pattern $\Psi(\varphi)$ of RA is obtained by applying the saddle-point technique to the evaluation of the integral expression for the radiation field. The directivity in the main beam direction, $\varphi=\varphi_o$, and the radiated power are obtained as, respectively

$$D = \frac{2Z_o\left|\Psi(\varphi_o)\right|^2}{kP_{rad}}, \qquad P_{rad} = \frac{Z_o}{\pi k}\int_o^{\pi}\left|\Psi(\varphi)\right|^2 d\varphi .$$

In the computations, we have chosen certain fixed reflector and feed geometry in order to concentrate our analysis on the effect of the earth. This is a $L=10\lambda$, $F/L=0.5$ reflector ($ka=62.8$, $\theta_{ap}=30^o$) symmetrically fed by CSP feed ($\beta=\varphi_o+\pi$, $kb=3.5$ (-13.29 dB edge illumination)) placed in the GO focus of reflector. The deviation of this circular reflector from a parabola is less than 0.09λ. Although the impedance parameter *Z* characterizing the earth is usually small, its value influences noticeably on the radiation and propagation of waves. Three basic cases are considered here:

1) $Z=0$: PEC plane that can be used as a model of the sea water interface. Radiation efficiency here is 100% as there is

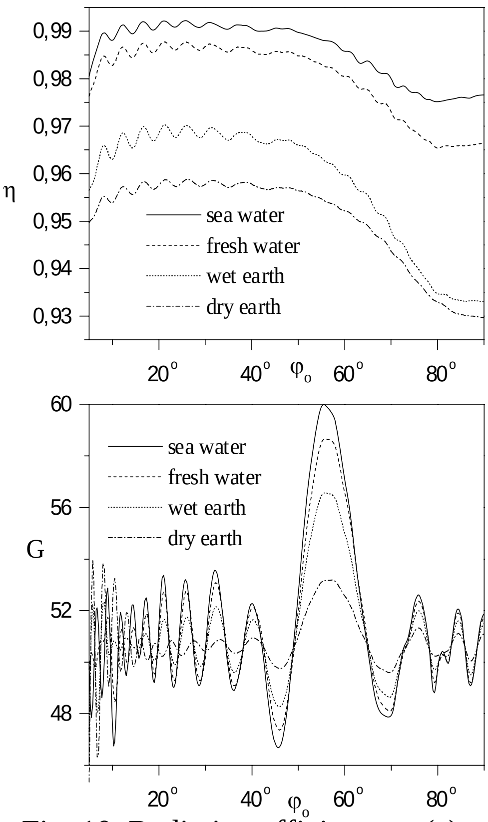

Fig. 10. Radiation efficiency η (a) and the gain of antenna *G* (b) for various types of the earth surface ($c/a=1.01$).

no loss due to the absorption or the surface waves. 2) $Z=-iY$: lossless impedance plane which can support a vertically-polarized surface wave; it can be used as an idealized model of a thin ice layer on the metal roof or a thin dry-sand layer on the wet substrate. In this case the total far field consists of two parts: the field radiated in the upper halfspace that carries power P_{rad} and the surface-wave field characterized by the powers $P_{sw\pm}$ carried by the right- and left-moving waves. 3) $Z=X-iY$: lossy impedance plane modeling the surface properties of arbitrary earth. In this case the power absorbed in the earth P_{abs} should be calculated in addition to the radiated power P_{rad}. Efficiency of radiation and gain are determined, respectively, as

$$\eta = P_{rad} / (P_{rad} + P_{abs});\ G = \eta D$$

Fig. 10 compares the effect of four types of lossy surfaces on the RA radiation: sea water: $\varepsilon=80$, $\sigma=1$ S/m, or $Z=0.0597-i0.0339$; fresh water: $\varepsilon=80$, $\sigma=10^{-3}$ S/m, or $Z=0.1118-i1.258\cdot10^{-4}$; wet earth: $\varepsilon=20$, $\sigma=10^{-2}$ S/m, or $Z=0.229-i10^{-2}$; and dry earth or sand: $\varepsilon=4$, $\sigma=10^{-3}$ S/m, or $Z=0.5-i1.123\cdot10^{-2}$. All the power characteristics are normalized to the radiation power of the same CSP feed located in the free space: $P_o=2Z_ok^{-1}I_o(2kb)$, where I_o is for the modified Bessel function. The presence of a flat earth does not have a strong effect on the radiated power. The absorbed power is small but increases for the large aiming angles φ_o, because then the both edge-spillover sidelobes hit the earth. This results in a lower radiation efficiency η of a zenith-looking antenna (Fig. 10a). The gain of antenna G can vary within 10% due to the earth properties, depending on the inclination, as in Fig. 10b. This means that such an effect may take place within one day due to drying the wet earth around a reflector.

Chapter 4 generalizes the approach proposed in Chaper 2 by applying the concept of analytical regularization to the solution of the problems of the wave scattering from dielectric cylinders of arbitrary smooth cross-section (Fig.11). After presenting the fields as single-layer surface potentials over the scatterer contour, a set of the Fredholm first-kind integral equations is obtained. On extracting and analytically inverting the circular-cylinder part of the singular integral operator, this equation has been reduced to the Fredholm second-kind infinite-matrix equation, which has been solved numerically with a guaranteed accuracy. The elements of the regularized matrix equation differ little, in the l2-norm, from the elements of the diagonal matrix, provided that the cylinder has a cross section close to the circle of radius a and is bounded by a contour with a curvature close to $1/a$. The center of gravity of the algorithm based on such a scheme moves on the efficient calculation of the double Fourier-series expansion coefficients of IE kernels. The algorithm of the Fast Fourier Transform is used to speed up the calculations.

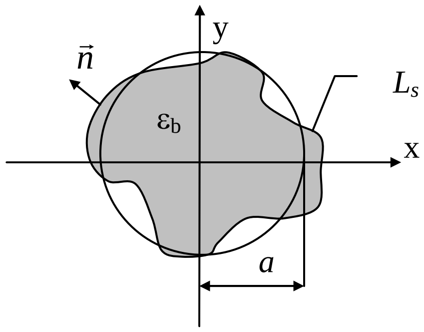

Fig.11. Cylinder of arbitrary cross- section

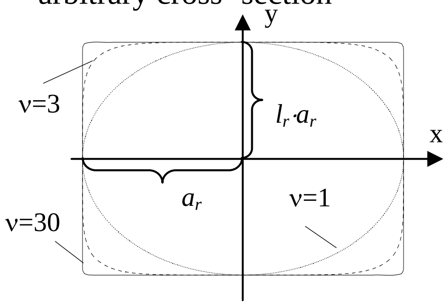

Fig. 12. "Super-rectangle"

Basic properties of the developed algorithm are studied and a comparison to the algorithm based on the inversion of the integral operator static part is done. In the computations, the contour of the cross section is characterized by the “super-rectangular” function (Fig.12). To illustrate the rate of the algorithm convergence, Fig.13 shows the error associated with the matrix truncation, as a function of the truncation number N. Fig.13 presents also the plots of the same error of the algorithm based on the extraction and analytical inversion of the static part. One can see that the convergence rates of both algorithms depend strongly on the cross section shape: the closer the contour is to a circle, the faster the error value tends to zero. Advantages that offer the algorithm based on the inversion of the circular cylinder part of IE’s become apparent if considering the scattering from objects larger then 5λ. Developed algorithm has been tested on the problem of a plane wave scattering from the free-

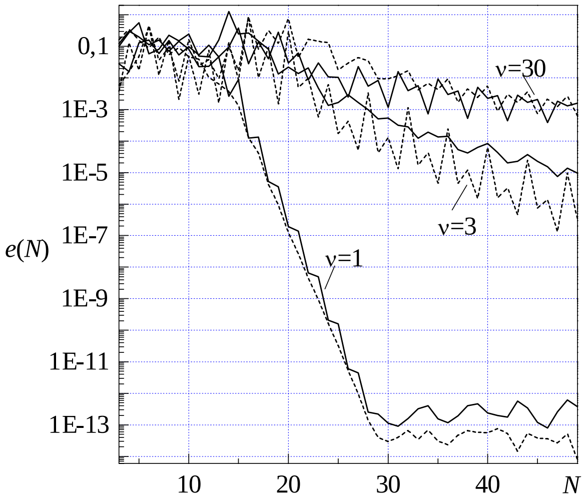

Fig. 13. The error associated with the matrix truncation
($ka_r = 4, l_r = 1.25, \varepsilon_b = 10 + 0.0001i$)

space cylinders of elliptical and rectangular cross-sections. Then it has been generalized to consider the problems of the surface-wave and the CSP-beam scattering from arbitrary cross-section cylinders embedded into a layered medium. Fig. 14 presents the plots of the normalized scattering patterns for the scattering of the dielectric waveguide surface wave from two cylinders of elliptical cross sections.

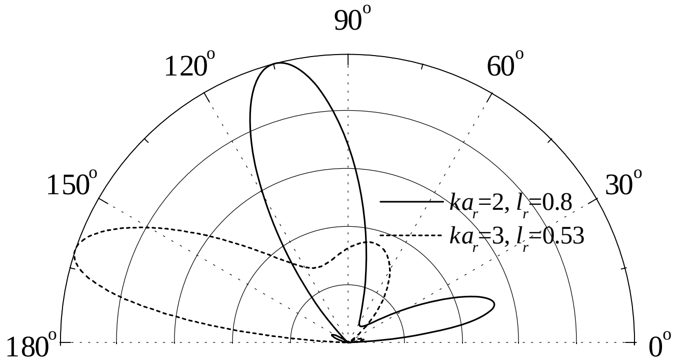

Fig.14. Normalized far-field scattering patterns
$ka = ka_r \cdot l_r$, $w/a = 0.01$, $d/a = 1$, $\varepsilon_b = 6$, $\varepsilon_s = 2.25$

Conclusions

The scattering of a dielectric layer surface wave from the dielectric resonators and metal cavity resonators, coupling of an external beam field into the same open waveguide by using dielectric couplers, as well as the radiation of a circular cylindrical reflector antenna in the presence of imperfect flat earth is considered. The surface potential approach and the method of analytical regularization are exploited to obtain the Fredholm second-kind matrix equations. The source directivity is included in the analysis by using the complex source point method.

Efficient numerical algorithms are developed with application to the design of bandstop filters and directional couplers. Transmitted and reflected power fractions, radiation and absorption losses, and coupling efficiencies are calculated for two polarizations. Sharp resonant phenomena are observed in the scattering of guided modes and beams from a dielectric cylinder at the WGE and WGH mode frequencies. It is shown that analyzed filters are dissipation filters rather than rejection ones, whatever small the loss tangent is of the material used. Effect of the excitation of the higher-order modes of the waveguide is studied. Removing the dielectric material from the central part of the resonator does not effect the $WGE(H)_{m,1}$ resonances unless the inner radius of the ring approaches the caustic, but eliminates parasitic resonances having multiple field variations along the radius. It is demonstrated that WG-mode directional coupler is able to convert at least 50% of the source beam power into a contra-directional surface wave.

It is shown that a slitted metal cavity offers a way to avoid the excessive radiation and minimize the electric size of the filter. An H-type resonance with low level of radiation losses are observed if the radius of cylinder is smaller than the wavelength. Our investigations prove the advantages offered by such resonators that can lead to their applications as surface-wave filters.

Various antenna features including the overall directivity, efficiency, gain, radiated and absorbed power fractions are calculated and compared with the free-space antenna characteristics. They show some phenomena not predicted by approximate techniques, e.g., the sidelobe level and hence the directivity can be both lower and higher than in the free space, depending on the antenna aiming angle and elevation; if antenna operates with a fixed aiming angle, its directivity can be improved simply by adjusting the plane of the local "earth" to reflect the spillover in the main beam direction; the difference in the directivity values of the same antenna over the sea and on the dry earth can be as great as 10% of the peak value, etc..

The developed method is generalized to the solution of the problems of the scattering from dielectric cylinders of arbitrary smooth cross-section shape embedded into a layered medium.

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