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SCATTERING AND ABSORPTION OF ELECTROMAGNETIC WAVES BY FLAT GRATINGS OF NOT PERFECTLY ELECTRICALLY CONDUCTING STRIPS

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GENERAL DESCRIPTION

This work deals with research into the problems of the E and H-polarized plane wave diffraction by flat gratings of free-standing of (i) resistive, (ii) magneto-dielectric, and (iii) impedance strips To simulate all these not perfectly electrically conducting strips, we systematically use two-side generalized boundary conditions supplemented with the condition of local energy integrability.

Timeliness of research. Along with wire gratings, various types of strip gratings have been widely used in the microwave, millimeter wave (mm) and sub-millimeter wave (sub-mm) devices. They are met as elements of polarization discriminators, polarization attenuators, polarization transformers, diffractometers, and interferometers. Sometimes they are also used as planar absorbers because of their absorption and resonance properties. However the most of theoretical papers have dealt so far with infinite-periodic gratings made of perfectly conducting (PEC) zero-thickness strips. Therefore the influence of the losses in imperfectly conducting strips on electromagnetic characteristics of the gratings made of such strips remained little studied. For comparison, the properties of the gratings made of imperfectly conducting circular cylinders were studied as far back as in the 1950-s due to the relative simplicity of corresponding diffraction problem solutions. Besides of traditional interest in the account of losses in connection with progress of communication, radar and measurement systems in microwave and mm-wave ranges, there has recently appeared a need of flat-panel coatings absorbing the electromagnetic waves in these ranges. Here, one of the most convenient and promising designs is a multilayered lossy resistive strip grating.

Theoretical analysis of the gratings consisting of *non-penetrable* imperfectly conducting strips could be based on the use of Leontovich impedance boundary conditions known from the 1940-s. However, such analysis has not been done so far because of the lack of convergent and grounded method of solution. For the partially *penetrable low-contrast* magneto-dielectric strips corresponding generalized boundary conditions appeared in the 1960-s in the papers of L. Vainshtein (Weinstein) and K. Mitzner. For *high-contrast* and metal ones they appeared in the 1980-s in the papers of T. Senior, Y. Grinberg, and G. Bushitt with co-authors. At the same time P. Petit and P. Mittra with co-authors for the first time studied the gratings made of *resistive* strips. However the computational algorithms developed by them did converge in the H-polarization case and lost efficiency in the case of the grating with narrow strips or slots in the E-polarization case. It should be noted that for the strip with finite width and zero thickness any boundary conditions must be supplemented with the condition of local energy integrability, to provide solution uniqueness.

Thus the investigation of realistic strip gratings of varying in wide range geometrical and material parameters, on the basis of reliable and efficient computational algorithms and correct mathematical methods of solution of corresponding boundary-value problems for the Maxwell equations, is a timely problem in theoretical radio physics. A solid foundation for the development of the above mentioned methods and algorithms can be seen in the concept of analytical regularization.

Relation to R&D programs and projects. The research related to this thesis has been done in the framework of R&D projects of IRE NASU, “Investigation of interaction of electromagnetic waves of sub-mm range with quasi-optical electromagnetic structures, substances, and biological objects” (code “Osnova,” #01.96U006114, 1998-2000) and “Quasi-optical and optical approaches, concepts, and methods for investigations in radio physics” (code Ort, #01.00U006440, 2001-2003).

Aims and tasks. The aims and tasks of the thesis are:

1. Reduction of two-dimensional (2-D) boundary-value problems related to the plane wave scattering by the infinite-periodic gratings of imperfectly conducting thin strips to infinite sets of linear algebraic equations of the Fredholm 2-nd kind (ISLAE-2) by means of consistent use of the analytical regularization concept on the basis of inversion of the static part of the problem operator.
2. Detailed analysis of the dependences of wave scattering and absorption characteristics on the frequency and grating parameters on the basis of developed algorithms.
3. Derivation of analytical formulas for the amplitudes of the scattered field spatial harmonics in the low-frequency range (so called Lamb's formulas) and their comparison with full-wave computations using ISLAE-2.
4. Search for the geometrical and material parameters of imperfect gratings, for example, of resistive and impedance strips, that provide efficient absorption of electromagnetic waves.

The object of research in the thesis is electromagnetic wave scattering and absorption phenomena. Considered are the problems of the E and H-polarized plane wave diffraction by infinite flat gratings of free-standing (i) resistive, (ii) material, i.e. magneto-dielectric, and (iii) impedance strips.

The methods of research used in the thesis are based on the analytical regularization concept. It has been found that, when solving diffraction problems concerning thin imperfect gratings, there appear two types of the dual series equations (DSE) for the amplitudes of the field spatial harmonics. DSE of the first type can be reduced to ISLAE-2 using the Riemann-Hilbert Problem solution (RHP). This method was proposed in 1962 by Z. S. Agranovich, V. A. Marchenko, and V. P. Shestopalov in the analysis of the problem of a plane wave normally incident on a flat PEC-strip grating. Since then it has been widely used for the analysis of various periodic zero-thickness PEC scatterers. DSE of the second type can be partially inverted by using the inverse Fourier transformation (IFT). In general case when a coupled set of DSE appears the both methods are used. As a result in each case the study of each scattering problem is reduced to a set of ISLAE-2 and further solved numerically.

Besides of convergent computations, the regularized nature of obtained ISLAE-2 has allowed to build their asymptotic solutions in the low-frequency range (so-called Lamb's formulas) and estimate their accuracy versus full-wave solution. Such long-wave asymptotics considerably simplify the analysis of reflection and transmission of plane waves by small-period gratings typical for applications.

Scientific novelty of obtained results is determined by the following considerations:

1. For the first time the generalized boundary conditions have been systematically used for simulation of the gratings made of thin imperfectly conducting strips of penetrable and impenetrable types,
2. For the first time the method of analytical regularization has been successfully applied to the solution of scattering problems associated with thin-strip resistive, magneto-dielectric, and impedance gratings,
3. It has been found that the dependence of resistive-strip grating absorption on the surface resistance has a wide maximum,
4. It has been shown that a penetrable small-period dielectric grating (unlike a PEC-strip grating) can not serve as a polarization discriminator,
5. New resonance effect has been found: strong absorption of the E- and H- polarized waves by the gratings made of thin dielectric lossy strips near the Rayleigh grazing points of the field spatial harmonics of higher orders; this can be used for polarization selection,
6. It has been shown that impedance gratings also have the same property mentioned above in the H-polarization case; if the strips are coated with a magnetic-type lossy coating at the

illuminated side of the strips, one can achieve a significant absorption in a wide range of frequencies.

Practical importance of obtained results. Although the beginning of the practical application of diffraction gratings made of conducting metal strips refers to the 1950-s, so far the theoretical investigations of their scattering characteristics have been devoted chiefly to the PEC-strip grating scattering problems. The analysis performed in this thesis has allowed to study the impact of losses on the scattering characteristics of the gratings with different material properties and thus deepened the understanding of the wave phenomena associated with realistic gratings. In particular it has been found and explained the effect of the resonance absorption near the grazing points of the field spatial harmonics of higher orders that is absent in the case of PEC-strip gratings. Besides, we have found geometrical, material, and electrical parameters of resistive-strip gratings suitable for design of efficient planar absorbers. It should be emphasized that the developed algorithms and programs have high versatility and efficiency because the use of the analytical regularization method guarantees fast convergence of numerical results.

Personal contribution of the candidate. All main results presented in the thesis belong to the author. Her contribution, in the co-authored papers [1, 3-12], is in the derivation of the basic equations, development of numerical algorithms, systematic computation of numerical simulations, discussion and interpretation of the numerical results. Her contribution to the paper [2] includes full amount of the above work related to the problem solution, obtaining numerical results, and their analysis.

Dissemination of the results. The results of this thesis have been personally presented by the author at the following scientific seminars “Radio physics and electronics of millimeter and sub-millimeter waves” at IRE NASU (Prof. V. K. Kiseliov); at the scientific seminars in the Nihon and Chuo Universities (Tokyo, 1999, 2002), Kumamoto University (Kumamoto, 2000, 2002), the National Institute of Telecommunications (Warsaw, 2000), and the Kyushu University (Fukuoka, 2002). They were also presented at the following international conferences:

- International Symposium of Applied Computational Electromagnetics Society (ACES-97), Monterey, USA, 1997,
- Sino-Japanese Joint Meeting on Optical Fiber Science and Electromagnetic Theory (0FSET'97), Wuhan, China, 1997,
- International Conference on Electromagnetics in Advanced Applications (ICEAA-97), Torino, Italy, 1997,
- International Conference on Mathematical Methods in Electromagnetic Theory (MMET*02), Kiev, Ukraine, 2002,
- International Workshop on Optical Waveguide Theory and Numerical Modeling (OWTNM-02), Nottingham, UK, 2002,
- International IEEE Symposium on Antennas and Propagation, San-Antonio, USA, 2002,
- Asia-Pacific Microwave Conference (APMC-02), Kyoto, Japan, 2002,
- International Kharkov Symposia of Physics and Engineering of Microwaves, MM and Sub-MM Waves (MSMW-01, MSMW-04), Kharkov, Ukraine, 2001, 2004.

Publications. The results of research have been published in 12 papers including 3 papers in technical journals [1-3] and 9 papers in the proceedings and digests of international conferences.

Structure and size of thesis. The thesis includes introduction, 4 chapters, conclusions, 3 appendices, and a list of literature sources which have been used. The total thesis size amounts 141 pages, from them 13 pages are for the list of the references (122 titles). The thesis includes 37 figures.

THESIS ESSENTIALS

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

Chapter 1 is a review of the literature relevant to the thesis. *The first subsection* is dedicated to the applications of diffraction gratings in physics and engineering of electromagnetic waves.

The second subsection presents a historical overview of the main stages of research into diffraction of waves by flat gratings made of both PEC and imperfectly-conducting strips and existing approaches to their analytical and numerical simulation.

The third subsection introduces the generalized boundary conditions (GBC), which are systematically used in the thesis for building numerical solutions to the scattering problems associated with infinite gratings made of thin resistive, magneto-dielectric, and impedance strips ($k_0\tau << 1$, where k_0 is the wavenumber in free space, τ is the strip thickness). GBC is a set of two equations linking the jumps in the limit values of the tangential components of electric and magnetic fields across a penetrable or impenetrable slab of the width τ with the average limit values of the fields. In the most general case, GBC have the following form:

$$\begin{aligned} \frac{1}{2}\left[\vec{E}_t^+ + \vec{E}_t^-\right] &= R\vec{n}\times\left[\vec{H}_t^+ - \vec{H}_t^-\right] + W\left[\vec{E}_t^+ - \vec{E}_t^-\right] \\ \frac{1}{2}\left[\vec{H}_t^+ + \vec{H}_t^-\right] &= -\,Q\vec{n}\times\left[\vec{E}_t^+ - \vec{E}_t^-\right] - W\left[\vec{H}_t^+ - \vec{H}_t^-\right]. \end{aligned} \tag{1}$$

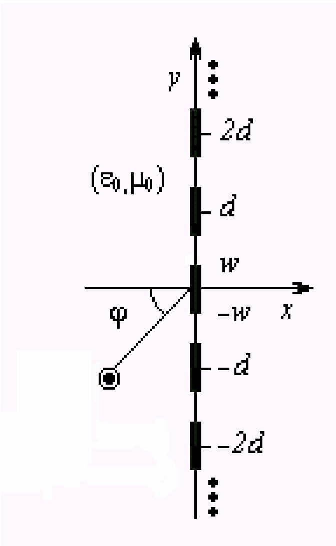


Fig.1. Plane strip grating in free space.

Here, the complex parameters R and Q have dimensionalities of the surface resistance and the surface conductivity, respectively. They are called the electric and magnetic resistivity, respectively, because the jump in magnetic (electric) field is the surface electric (magnetic) current induced on a thin magneto-dielectric slab. The dimensionless quantity W is the so-called cross-resistivity, which appears when the slab is non-uniform or multilayer.

In (1), $\vec{n}$ is the one-side unit vector normal to the slab interface, the subscript t means that corresponding vector has only tangential components, and the superscripts «–» and «+» refer to two faces of the slab: illuminated and shaded, respectively (see Fig. 1).

The fourth subsection deals with the methods of the diffraction theory based on analytical regularization which have been used in the thesis. In this subsection the significance and benefits of the method of analytical regularization have been explained and also the essential equations of the Riemann-Hilbert method for the duel series equations and the moment method with regularization for singular integral equations have been presented.

Chapter 2 is deals with the diffraction of time-harmonic ($\sim e^{+j\omega t}$) E and H-polarized plane electromagnetic waves by the grating made of *resistive strips* in free space.

The first subsection includes the problem formulation. As known, the resistive strip is an approximate model of either a strip made of imperfectly conducting metal with the thickness smaller than the skin-depth or a thin low-contrast dielectric strip. The electric resistivity is defined, respectively, as

$$R = \begin{cases} \zeta_0 / \tau\sigma, & \text{metal with } \tau << \delta \\ \zeta_0 / jk_0\tau(\varepsilon_r - 1), & \text{dielectric with } |\varepsilon_r - 1| << 1, \end{cases} \tag{2}$$

where $\zeta_0 = (\mu_0 / \varepsilon_0)^{1/2}$ is free space impedance, σ is the conductivity, $k_0 = \omega / c$, ω is the cyclic frequency, ε_r is the relative dielectric permittivity, and δ is the skin depth. The magnetic resistivity is assumed infinitely large, $|Q| = \infty$, so that the electric field is continuous, $\vec{E}_t^+ = \vec{E}_t^-$, and the cross-resistivity is absent, $W = 0$.

In the scattering problem, one has to find a *z*-component of the total electromagnetic field, $U = U_{inc} + U_{sc}$ (which is either E_z or H_z component depending on the polarization). The incident field function corresponding to the plane wave incident at the angle φ to the *x*-axis is given by $U_{inc} = e^{-jk_0(x\cos\varphi + y\sin\varphi)}$. For the uniqueness of the solution to the scattering problem, the unknown function U_{sc} must satisfy two-dimensional (2-D) Helmholtz equation off the strips, the boundary conditions for a resistive layer on the strips, the edge condition, which requires integrability of the energy flow through any surface enclosing an edge point, and the radiation conditions, which eliminates any waves that do not comply with the principle of radiation ("no sources of the scattered field at infinity").

As follows from the Floquet theorem, the grating periodicity along the *y*-axis leads to the quasi-periodicity of the total field that means, $U(x, y + d) = e^{-j\beta_0 d} U(x, y)$, where $\beta_0 = k_0 \sin\varphi$. Due to this fact, the scattered field can be expanded into a Floquet-Rayleigh series in terms of the so-called spatial harmonics,

$$\begin{Bmatrix} E_z^{sc}(x, y) \\ H_z^{sc}(x, y) \end{Bmatrix} = \sum_{n=-\infty}^{\infty} \begin{Bmatrix} a_n, & x > 0 \\ b_n, & x < 0 \end{Bmatrix} e^{-j(\alpha_n |x| + \beta_n y)}, \tag{3}$$

where a_n and b_n are the amplitudes of the scattered field *n*-th spatial harmonic in the transmission and reflection half-space, respectively, and $\alpha_n = (k_0^2 - \beta_n^2)^{1/2}$ and $\beta_n = \beta_0 + 2\pi n / d$ are their propagation constants along the *x*-axis and *y*-axis, respectively. Here, the radiation condition requires that either $\mathrm{Re}\,\alpha_n > 0$ or $\mathrm{Im}\,\alpha_n \le 0$.

The second and third subsections are present the scattering problem analyses for the H- and E-polarizations, respectively. The amplitudes a_n and b_n of the spatial harmonics are linked to each other by the dual set of the boundary conditions hold on the complementary sub-intervals of the elementary period, i.e. the resistive-type boundary conditions at the strip and the field continuity at the slot. As mentioned, the resistive conditions are given by the equations (1) for $R \neq 0$, $Q = \infty$, and $W = 0$.

In the H-polarization case, $b_n = -a_n$ and the coefficients b_n can be excluded from further consideration. The dual conditions at the elementary period, together with expansion (3), lead to a dual series equation (DSE) for determination of coefficients a_n. After using the analytical inversion of the static part of the DSE operator (i.e. the part corresponding to $k_0 d \to 0$), this equation is reduced to ISLAE-2.

In the case of E-polarization, the coefficients b_n can be also excluded from consideration because $b_n = a_n$. Here the static part of the corresponding DSE can be inverted analytically by using the Inverse Fourier Transformation (IFT). In either case the resulting equation has the form of a Fredholm second-kind infinite-matrix equation,

$$\sum_{n=-\infty}^{\infty} \left(\delta_{mn} + A_{E(H),mn} \right) a_m = B_{E(H),m}, \tag{4}$$

where δ_{mn} is Kronecker's delta.

The forth subsection deals with the analysis of numerical results. The solution of the ISLAE-2 truncated to a finite order *N* allows to determine the approximate coefficients a_n and b_n for the given values of the grating parameters and incident field, and convergence to exact values, if $N \to \infty$, is guaranteed by the Fredholm theorems. Thus, theoretically the accuracy is limited only by the digital precision of the computer used. The actual rate of convergence is demonstrated by the relative error curves in Fig. 2.

The curves in Fig.3 present the dependences of the reflected, transmitted and absorbed power fractions on the normalized value of electrical resistivity of the strips. They demonstrate existence of broad maximum of absorbance, in both polarizations, whose amplitude and position depend on the relative width of the strip and the angle of the plane-wave incidence. This is because the initial growth of absorption, with increasing *R*, is further cancelled by an increased transparency of the grating strips (see the first of conditions (1)). We have also considered the dependences of the transmitted, reflected, and absorbed power fractions on the electrical period of the grating, $\kappa = d/\lambda$ (i.e. the period normalized by the wavelength λ) and demonstrated that the absorbed power can be comparable with the scattered power and even exceed it.

The fifth subsection deals with the derivation of the so-called modified Lamb formulas (asymptotic formulas in the low-frequency range). It has been shown that the computation error in the absolute value of the reflection coefficient obtained by using these formulas does not exceed 5% relatively to exact full-wave solution at $\kappa < 0.3$ and $R/\zeta_0 > 1$ in the case of the E-polarization at any angle of incidence and the value of normalized strip width $2w/d$. In the case of the H-polarization the same is achieved at $\kappa < 0.3$ and $R/\zeta_0 < 1$.

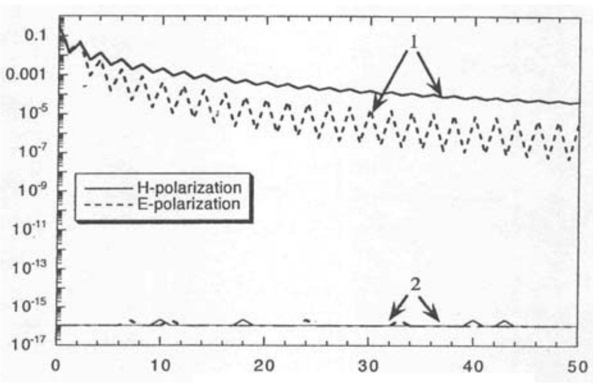


Fig.2. Normalized computation errors (1) and power conservation balance (2). $\kappa = 1.5$, $\varphi = 0^0$, $R = j$ as a function of the truncation number.

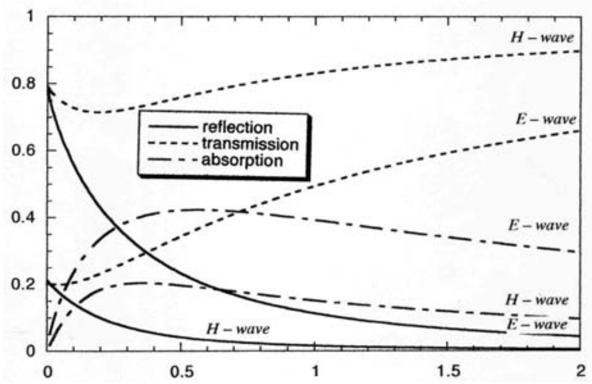


Fig.3. Power fractions for the plane-wave scattering by a resistive-strip grating versus the normalized strip resistivity value. $\varphi = 0^0$, $\kappa = 1.5$, $2w/d = 0.5$.

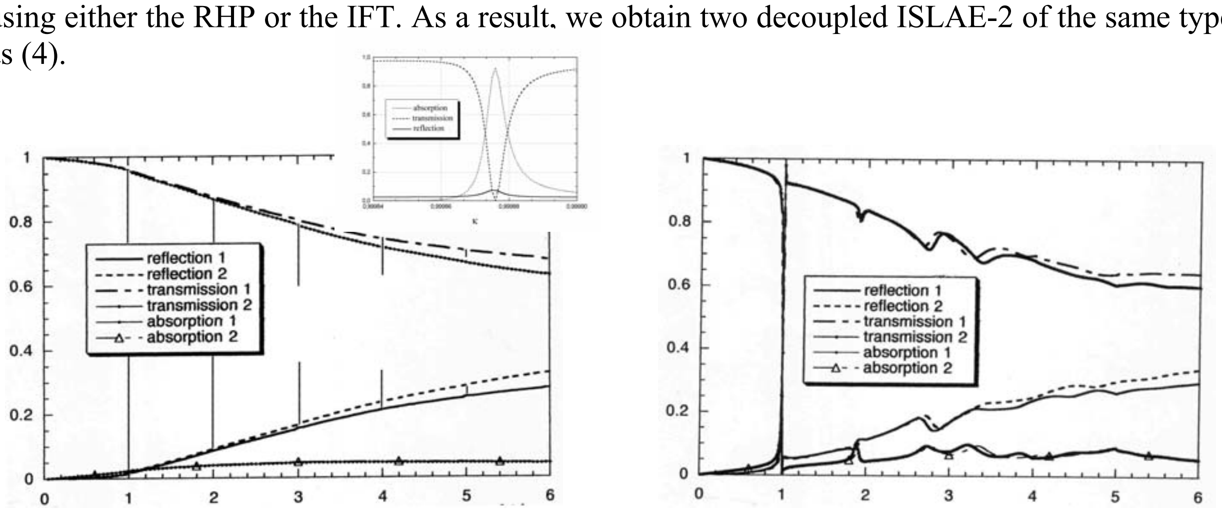
Chapter 3 is concerned with the diffraction of plane electromagnetic waves by the grating made of thin *dielectric strips* placed in free space.

The first subsection presents the problem formulation. The geometry of the problem is the same as in Fig.1. In the considered case both electric and magnetic resistivities are finite non-zero functions of the strip thickness, frequency, and material parameters. If the strip material is characterized with a high optical contrast, ($|\varepsilon_r \mu_r| >> 1$), then

$$R = -j(1/2)(\mu/\varepsilon)^{1/2}\cot\left(\sqrt{\varepsilon\mu/(\varepsilon_0\mu_0)}k_0\tau/2\right), \quad Q = -(1/2)j(\varepsilon/\mu)^{1/2}\cot\left(\sqrt{\varepsilon\mu/(\varepsilon_0\mu_0)}k_0\tau/2\right) \quad (5)$$

However the cross-resistivity W is zero provided that the strip is homogeneous. The other conditions involved into the scattering problem formulation to provide the uniqueness of solution remain the same as in the previous chapter.

The second subsection deals with the scattering problem solution for two cases of alternative wave polarizations, E and H. To determine the unknown coefficients a_n and b_n, we use the dual boundary conditions on elementary period composed of the GBC (1) with $R \neq 0, \infty$, $Q \neq 0, \infty$ and $W = 0$ at the strip and the field continuity at the slot. As a result, we obtain two decoupled DSEs for the unknown values of combinations $(a_n + b_n)$ and $(a_n - b_n)$, in either polarization. One of DSEs has the same properties as the DSE in the scattering of the E-polarized plane wave by a resisitive-strip grating considered in Chapter 2, and another DSE has the same properties as the DSE in the scattering of the H-polarized plane wave by a resistive-strip grating. As we have already dealt with such DSEs, the static part of each of them can be inverted by using either the RHP or the IFT. As a result, we obtain two decoupled ISLAE-2 of the same type as (4).



κ (a) κ (b)

Fig.4. Transmitted, reflected, and absorbed power fractions for the scattering by a dielectric-strip grating with ε_r=10-j versus κ. φ=0^0, $2w/d$=0.5, τ/d=0.01. Two models are compared: (1) high-contrast (solid lines) and (2) low-contrast, i.e., $R=R_{diel}$ (2) and $Q=\infty$ (dashed lines). (a) H-wave, (b) E-wave.

The third subsection deals with the analysis and interpretation of the numerical results. Fig. 4 demonstrates the values of the transmitted, reflected, and absorbed power fractions as a function of the electrical period of the dielectric-strip grating. A characteristic feature of these plots is that they have a generally similar character for both polarizations that is different from the PEC or constant resistivity strip-grating cases. Note that in the low-frequency limit, the strip grating is well transparent for an arbitrarily polarized plane wave and more power is absorbed than reflected. From these figures one may see that the low-contrast and high-contrast models agree well only in the low-frequency range. In case of the normal incidence for both polarizations the curves are monotonic, except the resonance peaks near the grazing points which are placed at $\kappa = 1,2,3...$. The most remarkable resonance is seen as a narrow and deep drop of transmission just below the grazing point of the ±1 Floquet harmonics ($\kappa = 1$). The resonance frequencies in E and H cases differ from each other. Zooming this area shows that here both

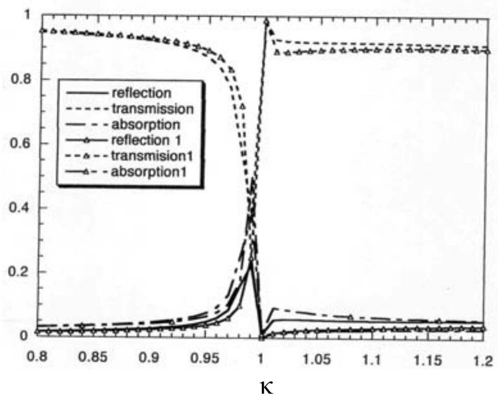


Fig.5. Power fractions for the E-wave scattering by a dielectric grating (Fig.4) but in the vicinity of the grazing point of the 1-st spatial harmonic. For comparison, similar data computed with the VIE technoque are presented by the marked curves.

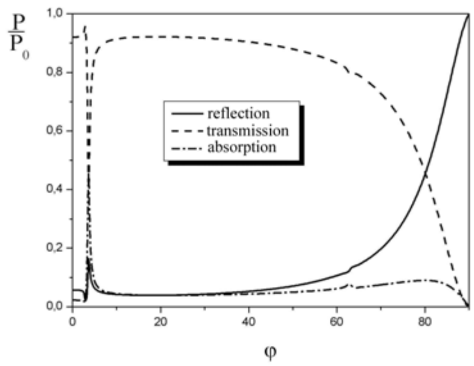


Fig.6. Power fractions for the E-wave scattering by a dielectric strip grating versus the angle of incidence. κ=1.05, 2w/d=0.5, τ/d=0.01, ε_r=10-j, μ_r=1.

reflection and absorption have sharp maxima and, for $\varepsilon_r = 10 - j$, the absorption exceeds the reflection in both H-polarization (Fig. 4) and the E-polarizations (Fig. 5) cases. Therefore the grating of thin dielectric strips with $\kappa = \kappa_{res} \approx 1$ can serve as a narrow-band isolating screen or polarization discriminator. Comparison of these values with the similar ones (marked with triangles in Fig.3) computed by the volume integral equation (VIE) method shows a remarkably good agreement validating our results. The resonance behavior of the dielectric grating characteristics at the frequencies slightly lower than that the grazing points of the higher-order spatial harmonics are explained by the excitation of specific natural oscillations of the grating caused by the periodicity of our scatterer Fig. 6 demonstrates that, if the plane-wave incidence angle varies, then this resonance effect is observed in a narrow sector of the angles; therefore it can be also used for the angular selection and screening.

The forth subsection deals with derivation of the modified Lamb formulas for the grating of dielectric strips. These formulas are obtained by using iterations in the same way as it has been done in Chapter 2. The low-frequency asymptotics agree well with the dependences computed by the full-wave solution, particularly if $\kappa < 0.5$ and large ε_r (μ_r) in the E-(H-)wave case. The error does not exceed 10% for $\kappa < 0.3$ and arbitrary values of the relative strip width $2w/d$ at the normal incidence.

Chapter 4 is concerned with the diffraction of plane electromagnetic waves by the grating of thin *impedance strips* (i.e. impenetrable and imperfect) located in free space. In general case, the impedances of the strip faces are different. The geometry of the problem is the same as in Fig.1.

The first subsection includes the problem formulation. The impedance strip appears, first of all, as a model of the imperfectly conducting metal strip having the thickness greater than the skin depth but smaller than the wavelength. In such a case, both strip faces have the same surface impedance, $Z^{\pm} = (1+j)\sqrt{\omega\mu/2\sigma}$. Another interesting for applications case is a PEC zero-thickness strip covered with thinner-than-wavelength ($k\tau^{\pm} << 1$) magneto-dielectric coatings, in general different from each other. If, additionally, the coating material has high contrast, $|\varepsilon_r^{\pm}\mu_r^{\pm}| >> 1$ then the corresponding surface impedances are

$$Z^{\pm}/\zeta_0 = j\sqrt{\mu_r^{\pm}/\varepsilon_r^{\pm}}\tan(\sqrt{\varepsilon_r^{\pm}\mu_r^{\pm}}k_0\tau^{\pm}) \quad (6)$$

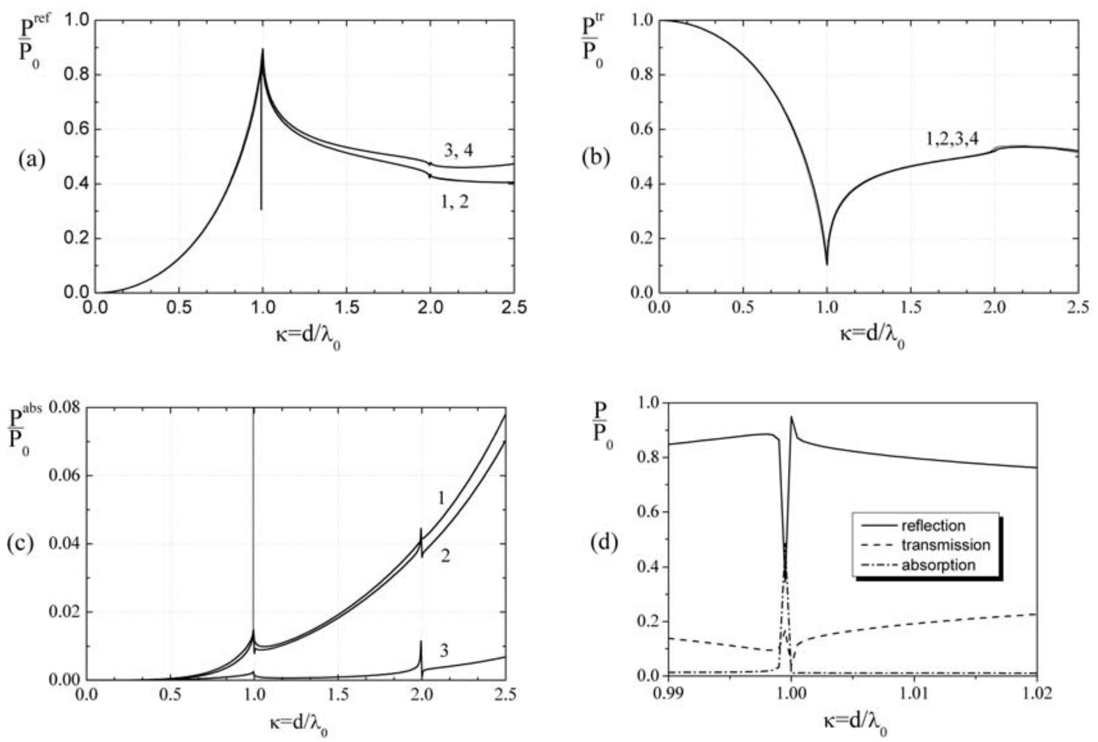


Fig.7 Reflected (a), transmitted (b), and absorbed (c) power fractions as functions of κ for the scattering of the H-wave from a coated grating with electric losses. $\varphi=0^0$, $\tau/d=0.01$, $2w/d=0.5$, $\mu_r^- = \mu_r^+ =1$, (curves 1) $\varepsilon_r^- = \varepsilon_r^+ =1-30j$, (curves 2) $\varepsilon_r^- =1-30j$, $Z^+=0$, (curves 3) $Z^-=0$, $\varepsilon_r^+ =1-30j$, (curves 4) are the same as for PEC grating. (d) is the same as (a)-(c) for the case (curves 1) in the vicinity of resonance.

In such a case the GBC (1) include all three resistivities with finite values of R, Q and W. However these resistivities are coupled together by the condition of impenetrability; they relate to the surface impedances (for $Z^+ \neq Z^-$) as

$$R = \frac{Z^+ Z^-}{Z^+ + Z^-}, \quad Q = \frac{1}{Z^+ + Z^-}, \quad W = \frac{1}{2}\frac{Z^+ - Z^-}{Z^+ + Z^-}, \tag{7}$$

Note that the cross-resistivity vanishes if the face impedances of the strip are identical.

The second subsection presents the derivation of the basic equations for the plane-wave scattering by impedance-strip grating in the cases of the H- and the E-polarizations. To obtain the Fredholm second-kind matrix equations for the coefficients a_n and b_n, we use two sets of dual boundary conditions on complementary intervals of elementary period (i.e. at the strip and at the slot) similarly to the study of the gratings of resistive and dielectric strips. At the strip, GBC given by (1) are imposed and, at the slot, the condition of the electric and magnetic fields continuity are requested. These conditions, after substitution of (3) and (7), lead to two coupled pairs of DSE with the unknowns expressed in terms of a_n and b_n amplitudes. The analytical inversion of the static parts of these equations by using the RHP and the IFT leads to the coupled ISLAE-2 of type (4) which allows convergent and stable numerical solution with the accuracy controlled by the matrix truncation number. If, additionally, the face impedances are identical then $W = 0$ and resulting ISLAE-2 decouple from each other.

The third subsection deals with the analysis of the numerical results. Fig. 7 demonstrates the frequency dependences of the power fractions for the scattering of the H-polarized plane wave by the grating of PEC strips having one or both faces covered with thin material coatings

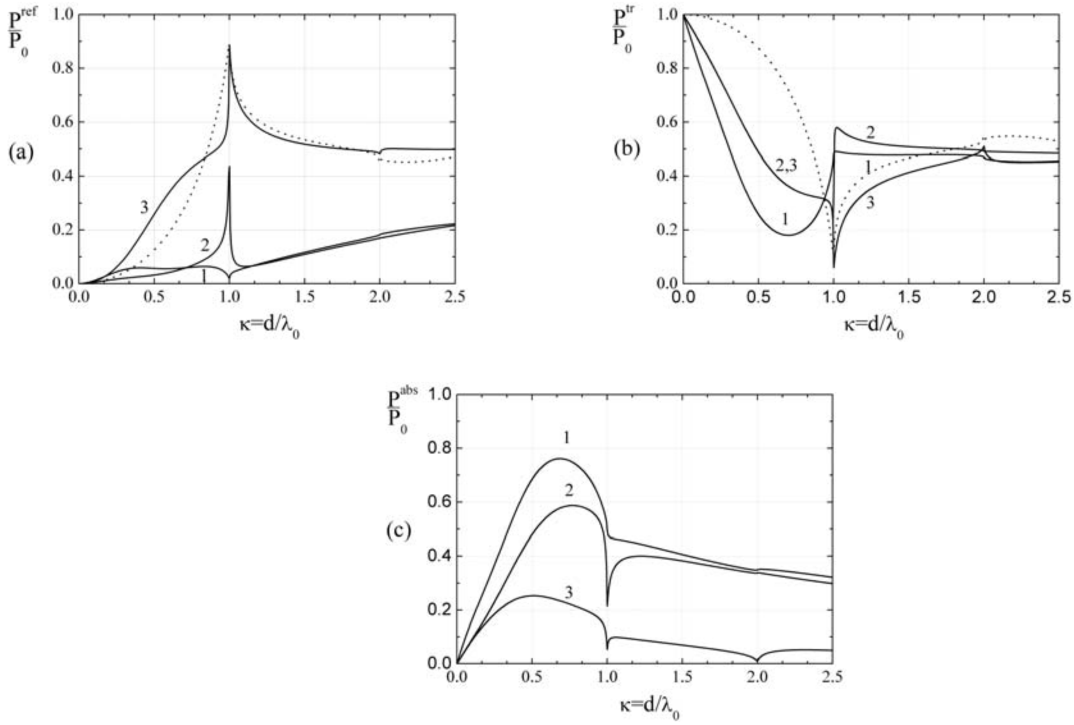


Fig. 10. Reflected (a), transmitted (b), and absorbed (c) power fractions as functions of κ for the scattering of the H-wave from impedance grating with magnetic losses. $\varphi=0^0$, $\tau/d=0.01$, $2w/d=0.5$, $\varepsilon_r^-=\varepsilon_r^+=1$, (curves 1) $\mu_r^- = \mu_r^+ = 1-30j$, (curves 2) $\mu_r^- = 1\text{-}30j$, $Z^+=0$, (curves 3) $Z^-=0$, $\mu_r^+=1\text{-}30j$. Dashed lines are the same as for PEC grating.

having large *dielectric* losses. These strips are characterized by two equal (curves 1) or different surface impedances (curves 2 and 3), respectively. Similarly to the case of a PEC-strip grating without coating, almost total transmission is observed in the low-frequency limit (both transmission and absorption are close to zero). Thus, small-period $(d << \lambda)$ impedance strip grating behaves like a PEC-strip grating, i.e. is almost transparent for the H-polarized wave.

At the same time, Fig.7 shows a sharp drop in reflectance and increase in absorbance in the narrow band just below the frequency $\kappa = 1$ (i.e., $d = \lambda$ for normal incidence), i.e. where the ± first Floquet harmonics are just before grazing. This resonant behavior is similar to that founding Chapter 3 for dielectric-strip strips and is caused by the excitation of the periodicity-induced natural oscillations of the grating.

Fig. 8 shows frequency characteristics of the power fractions for the H-wave scattering by the impedance grating modeling PEC-strip grating with strips covered with a *lossy magnetic* coating. One can see again that in the low-frequency limit a magnetic-material coated strip grating is completely transparent for the H polarization. However, now absorption resonances in the vicinity of the grazing frequencies are completely suppressed (compare Figs. 7 and 8). This can be explained by the stronger dependence of the resonance Q-factors on μ than on ε. Besides, at the higher frequencies the absorbance for the strip grating with imperfect magnetic coating of strips becomes much greater than for the same grating with dielectric coating. This is because in the case of the PEC-strips only magnetic field is not small near a strip and hence is sensitive to the presence of magnetic-type absorber placed near to strip. Unlike this, the electric field tangential component is zero at the PEC strip and, correspondingly, is not sensitive to the presence of thin coating of any type.

The forth subsection deals with modified Lamb's formulas for the grating of impedance strips. They have been derived from the resulting coupled ISAE-2 using the iterations similarly to Chapter 2. A comparison of these asymptotics with the full-wave solutions for the reflectance, transmittance and absorbance is discussed.

CONCLUSIONS

1. The method of analytical regularization based on the GBC in combination with the RHP and the IFT has been successfully applied for solving the problems of plane electromagnetic wave scattering by the gratings made of thin resistive, magneto-dielectric and impedance strips located in free space; the corresponding numerical algorithms use the truncated ISLAE-2 for the amplitudes of spatial field harmonics (or their combinations) and have guaranteed convergence.
2. It has been found that the dependence of the resistive grating absorption on the surface resistance has a broad maximum.
3. It has been shown that a small period dielectric grating made of thin strips can not serve as polarization selector (unlike PEC and well-conducting metal strip gratings).
4. The effect of resonance absorption has been found in the case of both the E- and the H-polarized wave incident on the grating made of thin dielectric strips near the grazing points of the higher-order spatial harmonics; this can be used for the frequency and polarization discrimination.
5. It has been found that the gratings made of well-conducting metal strips with the thickness greater than the skin-depth have negligible losses except of the resonance absorption of the H-polarized waves near the grazing points of the higher-order spatial harmonics.
6. It has been shown that the gratings made of metal strips with thin lossy material coating can have significant losses if absorbing coating has magnetic features and covers the illuminated face of the grating.
7. The modified Lamb formulas (asymptotics for $\kappa = d / \lambda < 1$) for all types of the considered strip gratings have been derived, valid for the wide range of their parameters; they have good agreement with the results of the full-wave numerical solution.

Main publications related to the thesis

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