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THE WAVEGUIDE TECHNIQUE OF MEASUREMENT OF THE COMPLEX PERMITTIVITY OF MATERIALS

Applied Electromagnetics and Circuit Theory

Introduction. Researches of dielectric properties of materials and behaviour of its complex dielectric permeability depending on various factors (temperature, pressure, intensity and frequency of electric field, etc.) have now the important scientific and practical value. It allows not only to find out a structure of its molecules but also enables to acquire necessary knowledge for making of new materials with the set properties for various areas of industrial production. Now among variety of dielectric properties diagnostics methods of materials the most actual ones are methods, which use interaction of electromagnetic fields with objects of research.

These methods of the dielectric properties measurement of materials use registration of changes of parameters of the electromagnetic waves which interact with the object and cover a frequency band from 1 MHz up to 1 THz. The variety of the existing methods is caused by the wide frequency band. A classification of the methods is presented as follows

the measurement methods in the time and frequency domain;

the measurement methods in the free space and with use of transmission lines;

the measurement methods, which use registration of transmission parameters and resonance parameters;

the measurement methods at discrete frequencies and broadband methods.

The majority of the measurement methods in the time domain use the analysis of an input impedance of a coaxial cell a manufacturing of which has no difficulties. The measurements in the time domain are usually carried out at frequencies only up to 10 GHz as at the further growth of frequency its sensitivity is reduced [1, 2]. These methods provide measurements in the wide frequencies band due to reduction of accuracy. For increase of the accuracy of the complex dielectric permeability measurements, it is especial in case of dielectric materials with small losses use measurements in the frequency domain [3, 4].

The measurement methods in a free space use the analysis of a transmission parameter of electromagnetic waves through a tested sample. Ones are effective in a case of solid materials [5] which it is easy to input in a zone of the measurements, and are the reason of problems in a case of liquids. Using of the transmission lines simplifies the measurements problem as in this case there are no difficulties of designing of the electrodynamic structures which include a container (for example a tube) for the tested material [6]. This feature is effectively applied in the measurements methods which use a registration of parameters of a resonance [7] or a transmission [8]. However the resonant methods which have high sensitivity use the simplified models of electrodynamic structures and require using correction factors [9]. At realization of the methods based on the registration of the transmission parameters, such difficulties do not appear, as there are exact models of the structures which are the regular transmission lines with the inclusions [10]. Application of vector network analyzers (VNA) allows using the methods in a wide frequencies band. It is important enough at research of the dielectric materials parameters in the real time in the scientific purposes for diagnostics of a condition of biological objects, for synthesis of dielectric materials with the set properties and for the control of their qualitative structure in manufacture, for example, the percentage of water in various liquids.

The purpose of the paper is development of the measurement method of the materials dielectric permeability at the microwave frequencies by results of measurement of electromagnetic waves scattering parameters in the directing structure (a waveguide sensor).

Formulation. The dielectric properties of materials are described by the complex dielectric permeability $\dot{\varepsilon} = \varepsilon' + j\varepsilon''$ in case of the time dependence submitted by a multiplier $e^{-j\omega t}$. This parameter is included into Maxwell's equations which describe the relation between vectors of electric both magnetic field and its interaction with medium. Use of the equations allows to solve a problem of the electromagnetic waves scattering at the electrodynamic structure as the waveguide sensor, which contain sample of the tested material, and to determine a matrix of S-parameters. The problem of the material complex dielectric permeability determination is a problem of the electromagnetic waves scattering parameters measurement results identification (reflection coefficient $\dot{S}_{11}$ and transmission coefficient $\dot{S}_{21}$) at the electrodynamic structure, containing the researched sample of the material, with results of the mathematical modeling wave processes in this structure (calculation of the scattering matrix parameters $\dot{S}_{11}$, $\dot{S}_{21}$) which is solved with use of minimization methods. The repeated solution of a direct electrodynamic problem of the scattering on the waveguide sensor and comparison of the calculation results and the measurement results are executed to calculate an error function $e(\dot{\varepsilon})$ at the each iteration. Initial approximations for the required parameters ε' and ε'', which are the start data for the solution of the direct problem, get out on the basis of the aprioristic data about the material properties and change on each iteration by the calculation results of value of the goal function

$$U(\dot{\varepsilon}) = \sum_{i} \sum_{n} \left| e_{ni}(\dot{\varepsilon}) \right|^2 , \qquad (1)$$

where n=1, …, 4 is the index corresponding to the real and imaginary parts of the reflection and transmission coefficients; i=1, …, M is the index corresponding to M discrete values of frequency for which the measurements execute.

The calculations speed and the identification accuracy of determined characteristics depend on the exactitude of the direct problem solution, the efficiency of the optimization methods and the accuracy of measurement of the S-parameters matrix.

To determine the complex dielectric permeability of materials at microwave frequencies with use of the reflection method it is necessary to execute the next step

to choose an optimum configuration of the sensor, allowing to reduce a tool error of measurement of the scattering parameters, and to take into account absorbing properties of a tested material which depend on value of the complex dielectric permeability;

to develop exact mathematical model of the main mode diffraction at the waveguide sensor;

to formulate the inverse problem of determination $\dot{\varepsilon}$ by the measured values of the reflection and transmission coefficient, to determine goal function;

to execute numerical researches of the goal function in a required interval of values $\dot{\varepsilon}$ and geometrical sizes of the sensor;

to select the most effective method of the solution of the inverse problem (optimization of the goal function) by the known form of the goal function;

to study the determination error of the complex dielectric permeability.

Waveguide sensor. The research of the properties materials including liquids with use of transmission line demands to take into account a number of features. First, it is necessary to have a hermetic container for a premise of a liquid; second, process of filling of the container should be technological enough, allowing executing measurements in the real time. The sensor as a dielectric tube placed in the rectangular waveguide in parallel its narrow walls, as shown on fig. 1, satisfies to the requirements in the best way.

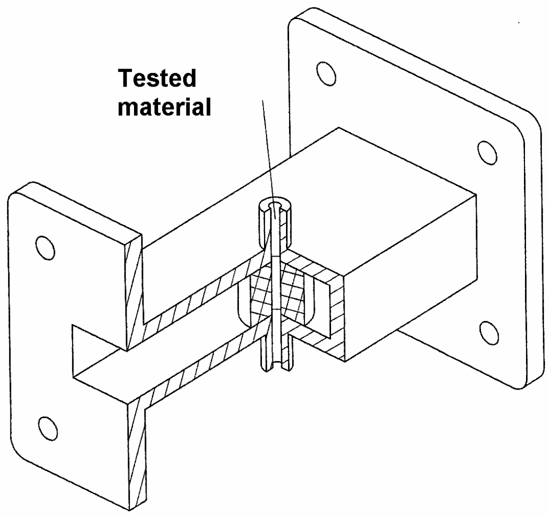

Fig. 1. Structure of the waveguide sensor

It is possible to dose out the tested material (placed in the waveguide) to obtain the values of the scattering parameters providing the minimal tool error in the sensor. It is achieved by a corresponding choice of the tube diameters. For example, for high loss materials need to use the tube with small diameters, for low loss materials - with big diameters.

Direct electrodynamic problem. The solution of the scattering problem of H_{10}-mode by the dielectric tube filled with the tested material, placed in the rectangular waveguide in parallel its narrow walls is obtained in [11]. The elements of the scattering wave matrix are determined by expressions

$$S_{11} = \frac{4}{a\beta_{10}} \sum_{n=-\infty}^{\infty} (-1)^n x_n J_n(k_0 r_2) \sin\left(\pi\xi - n \arcsin\frac{\pi}{k_0 a}\right), \qquad (2)$$

$$S_{21} = 1 + \frac{4}{a\beta_{10}} \sum_{n=-\infty}^{\infty} x_n J_n(k_0 r_2) \sin\left(\pi\xi + n \arcsin\frac{\pi}{k_0 a}\right), \qquad (3)$$

where a is the waveguide width, r_2 is the dielectric tube external radius, $\beta_{10} = \sqrt{k_0^2 - (\pi/a)^2}$, $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ are the H_{10}-mode propagation constant and the wavenumber, ε_0, μ_0 are the dielectric and magnetic permeability of the medium in the waveguide, $\xi = x_0/a$, x_0 is the distance from the waveguide narrow wall up to the tube axis.

The unknown complex coefficients x_n are the solution of infinite system of linear algebraic equations, which are described by the expressions

$$x_n + G_n \sum_{v=-\infty}^{\infty} \alpha_{n,v} x_v = G_n F_n; \quad n, v = 0, \pm 1, \pm 2, \ldots, \pm\infty, \qquad (4)$$

where $$G_n = \left[\frac{Y_n'(k_2 r_2)}{Y_n(k_2 r_2)}\sqrt{\frac{\mu_0 \varepsilon_2}{\varepsilon_0 \mu_2}} - \frac{J_n'(k_0 r_2)}{J_n(k_0 r_2)}\right]\left[\frac{Y_n'(k_2 r_2)}{Y_n(k_2 r_2)}\sqrt{\frac{\mu_0 \varepsilon_2}{\varepsilon_0 \mu_2}} - \frac{H_n^{(1)\prime}(k_0 r_2)}{H_n^{(1)}(k_0 r_2)}\right]^{-1}, \qquad (5)$$

$$\alpha_{n,v} = \frac{J_v(k_0 r_2)}{H_n^{(1)}(k_0 r_2)}\left\{\left[1 + (-1)^{v-n}\right]\sum_{\alpha=1}^{\infty} H_{v-n}^{(1)}(D\alpha) - \sum_{\alpha=1}^{\infty} H_{v+n}^{(1)}\left[D(\alpha - \xi)\right] - \right.$$

$$\left. - (-1)^{v+n} \sum_{\alpha=1}^{\infty} H_{v+n}^{(1)}\left[D(\alpha + \xi)\right]\right\}, \qquad (6)$$

$$F_n = -\frac{\sin\left(\pi\xi + n \arcsin\dfrac{\pi}{k_0 a}\right)}{H_n^{(1)}(k_0 r_2)}, \qquad (7)$$

$$Y_n(k_2 r_2) = J_n(k_2 r_2) - f_n N_n(k_2 r_2), \qquad (8)$$

$$f_n = -\frac{J_n(k_2 r_1)}{N_n(k_2 r_1)}\left[\frac{J_n'(k_2 r_1)}{J_n(k_2 r_1)} - \sqrt{\frac{\mu_2 \varepsilon_1}{\varepsilon_2 \mu_1}}\frac{J_n'(k_1 r_1)}{J_n(k_1 r_1)}\right]\left[\frac{N_n'(k_2 r_1)}{N_n(k_2 r_1)} - \sqrt{\frac{\mu_2 \varepsilon_1}{\varepsilon_2 \mu_1}}\frac{J_n'(k_1 r_1)}{J_n(k_1 r_1)}\right]^{-1}, \qquad (9)$$

J_n, N_n and $H_n^{(1)}$ are Bessel, Neumann and Hankel functions of n-th order and J_n', N_n' and Y_n' are the derivatives of J_n, N_n and Y_n; $k_1 = \omega\sqrt{\varepsilon_1 \mu_1}$, ε_1, μ_1, $k_2 = \omega\sqrt{\varepsilon_2 \mu_2}$, ε_2, μ_2 are the wavenumber, complex dielectric and magnetic permeability of the tested material and the tube material accordingly; $D = 2k_0 a$.

The mathematical substantiation of the problem solution is given in [11], where resolvability by a reduction method of the system (4) is proved. The characteristics dependences of an scattered field on parameters of the dielectric tube with a tested material ε_1, μ_1, ε_2, μ_2 is concluded in the coefficients $\alpha_{n,v}$, G_n. To calculate ones, the cylindrical functions J_n and N_n of the complex arguments are used, a calculation algorithm with accuracy of the order 10^{-14} for which is offered in [12]. The parameters

S_{11} and S_{21} are calculated with a margin error not worse 10^{-6} with the order of truncation of the system $N = 10$.

Inverse problem. In inverse problems the information about electrodynamic characteristics of a structure is initial, and its electrophysical parameters are required to determine, as against the direct problems in which the electrodynamic characteristics of the structure with the set electrophysical and geometrical parameters are required to determine. The parameters are the real ε' and imaginary ε'' parts of the complex dielectric permeability of the tested material which is placed inside the waveguide sensor for our case. Such problems, as a rule, are incorrect as in most cases ones do not meet the requirements to uniqueness of the solution and its stability because an error of measurement of the scattering parameters obtained in the experimental way have a place. In this case small changes of the initial data can result in the big changes of the solution which in turn do not allow to obtain uniqueness of the solution in the limits of the set accuracy. A solution of the problems demands to execute regularization as a rule.

The goal function which use for definition $\dot{\varepsilon}$ is determined to estimate of necessity of regularization and to study its kind. According to expression (1) the scalar function $U(\dot{\varepsilon})$ is the sum of errors between the measured $\dot{S}_{11ms}(\dot{\varepsilon})$, $\dot{S}_{21ms}(\dot{\varepsilon})$ and calculated $\dot{S}_{11cl}(\dot{\varepsilon})$, $\dot{S}_{21cl}(\dot{\varepsilon})$ values of the scattering matrix elements, where $\dot{\varepsilon}$ is the complex dielectric permeability of the tested material.

The error function is submitted as a difference

$$e(\dot{\varepsilon}) = S_{cl}(\dot{\varepsilon}) - S_{ms}(\dot{\varepsilon}), \qquad (10)$$

where S is one from the next parameters $\mathrm{Re}(\dot{S}_{11})$, $\mathrm{Im}(\dot{S}_{11})$, $\mathrm{Re}(\dot{S}_{21})$, $\mathrm{Im}(\dot{S}_{21})$.

The error vector which takes into account the listed above parameters, is submitted as

$$\vec{e}(\dot{\varepsilon}) = [e_1(\dot{\varepsilon}), e_2(\dot{\varepsilon}), e_3(\dot{\varepsilon}), e_4(\dot{\varepsilon})]^T, \qquad (11)$$

where indexes 1, 2, 3, 4 correspond to the real and imaginary parts of the reflection and transmission coefficients accordingly.

If to minimize the errors between measured $\dot{S}_{11ms}(\dot{\varepsilon})$, $\dot{S}_{21ms}(\dot{\varepsilon})$ and calculated $\dot{S}_{11cl}(\dot{\varepsilon})$, $\dot{S}_{21cl}(\dot{\varepsilon})$ values at M frequencies points, the error vector is represented as

$$\vec{e}(\dot{\varepsilon}) = [e_{11}(\dot{\varepsilon}), e_{21}(\dot{\varepsilon}), e_{31}(\dot{\varepsilon}), e_{41}(\dot{\varepsilon}), \ldots, e_{1M}(\dot{\varepsilon}), e_{2M}(\dot{\varepsilon}), e_{3M}(\dot{\varepsilon}), e_{4M}(\dot{\varepsilon})]^T. \qquad (12)$$

The goal function (1) is represented by the error vector (12)

$$U(\dot{\varepsilon}) = [\vec{e}(\dot{\varepsilon})]^T \vec{e}(\dot{\varepsilon}). \qquad (13)$$

The computer program solving the final system of equations (4), calculating the reflection and transmission coefficients (2), (3) and the goal function (13) has been developed.

The behaviour of the goal function for the test waveguide sensor filled with the tested material is investigated to select a minimization method.

The test waveguide sensor has the following geometrical parameters: $a = 23$ mm; $b = 10$ mm, that corresponds to section of a standard waveguide of the 3 sm range of wavelengths; position of the tube in the waveguide is central $x_0/a = 0{,}5$; the tube material is Teflon, the relative dielectric permeability of which is $\dot{\varepsilon}_2 = 2{,}0 + j0{,}0001$; the internal radius of the tube is $r_1/a = 0{,}0217$ or $r_1 = 0{,}5$ mm; the external radius of the tube is $r_2/a = 0{,}0435$ or $r_2 = 1{,}0$ mm; the tested material is water, the relative dielectric permeability of which is $\dot{\varepsilon}_1 = 61{,}5 + j31{,}4$.

As the measured values of the real and imaginary making parts of the reflection and transmission coefficients the values of the scattering matrix parameters of the test waveguide sensor filled with water calculated with use of the developed model for the frequency $\Delta = f/f_c = 1{,}5$, where f_c is the waveguide critical frequency for the basic H_{10}-mode are used: $\mathrm{Re}(\dot{S}_{11ms}) = -0{,}5620511551$; $\mathrm{Im}(\dot{S}_{11ms}) = -0{,}1291397411$; $\mathrm{Re}(\dot{S}_{21ms}) = 0{,}4368646271$; $\mathrm{Im}(\dot{S}_{21ms}) = 0{,}1313488816$.

The surface and level lines of the bidimentional goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ calculated at the same frequency, for ranges of values $\varepsilon' = [10 \ldots 120]$; $\varepsilon'' = [10 \ldots 120]$, are shown at fig. 2 and fig. 3, accordingly.

In the specified ranges of values ε' and ε'' the goal function $U(\dot{\varepsilon})$ has a single minimum; the level lines are represented by practically circles, and at small values $U(\dot{\varepsilon})$ the circles are concentric with the center in a point of a minimum with coordinates $\varepsilon' = 61{,}5$; $\varepsilon'' = 31{,}4$. The problem of the search of minimum of the researched goal function $U(\dot{\varepsilon})$ is well caused and may be solved with use gradient methods of optimization.

Numerical results. Effect on the measurement error of frequency points quantity and the basic error of frequency setting by a VNA oscillator, the basic error of parameters measurement $\mathrm{Re}(\dot{S}_{11})$, $\mathrm{Im}(\dot{S}_{11})$, $\mathrm{Re}(\dot{S}_{21})$, $\mathrm{Im}(\dot{S}_{21})$ and also dispersion of the geometrical sizes of the waveguide sensor is studied.

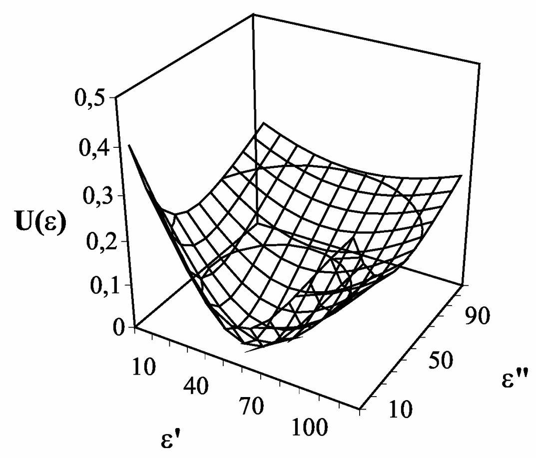

Fig. 2. The surface of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}5$

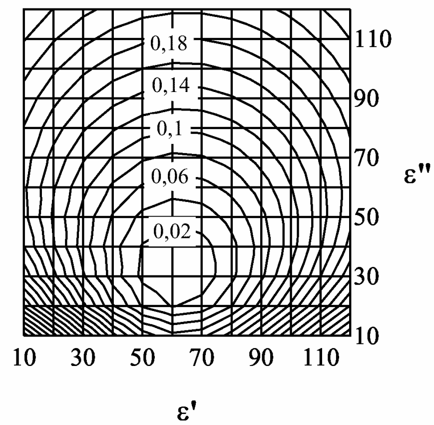

Fig. 3. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}5$

The geometrical sizes of the test waveguide sensor which given above, the complex dielectric permeability of water, the values of the scattering matrix parameters given in Table 1 were used as initial parameters.

Results of calculation of the goal function $U(\dot{\varepsilon})$ with use of values of the scattering parameters at one and three frequency points show, that the goal function surface form does not depend on frequency points quantity, the range of its values increases approximately three times. Procedure of minimization, graphic representation the execution results of which is presented on fig. 4, 5, shows, that at achievement by the goal function of value $U(\dot{\varepsilon}) = 5 \times 10^{-6}$ the complex dielectric permeability has size $\dot{\varepsilon} = (61{,}5 \pm 0{,}25) + j(31{,}4 \pm 0{,}25)$ in a case with one frequency point and $\dot{\varepsilon} = (61{,}5 \pm 0{,}15) + j(31{,}4 \pm 0{,}15)$ in a case with three frequency points.

Table 1

The values of the complex reflection and transmission coefficients corresponding to three frequency points on which calculation of the goal function was executed

Parameter	Δ		
	1,3	1,5	1,7
$Re(\dot{S}_{11ms})$	–0,5206047787	–0,562051155	–0,5989480916
$Im(\dot{S}_{11ms})$	0,1986911028	0,1291397411	0,0252998900
$Re(\dot{S}_{21ms})$	0,4788266225	0,4368646271	0,3992101103
$Im(\dot{S}_{21ms})$	0,1999023813	0,1313488816	0,0288582762

The determination error of the dielectric permeability by results of measurement of the complex reflection and transmission coefficients of at several frequency points may be reduced, but it will result in calculation time increase.

To estimate the measurement error of the complex dielectric permeability which is caused by the basic error of the frequency setting of a VNA oscillator, the goal function minimization at the frequency points $\Delta = 1{,}4955$ and $\Delta = 1{,}5045$, corresponding to the basic error of the frequency setting $\pm 0{,}1\%$ is executed. The executing results of the search procedure of complex dielectric permeability determination are shown at fig. 6, 7. From the diagrams it is followed, that the procedure of goal function minimum search gives values $\dot{\varepsilon} = 61{,}3 + j31{,}15$ and $\dot{\varepsilon} = 61{,}7 + j31{,}65$. If to stop search procedure at achievement by the goal function of value $U(\dot{\varepsilon}) = 5 \times 10^{-6}$ the found sizes of the complex dielectric permeability are located inside of the circles with radiuses $0{,}25$ and the centers with the coordinates $(61{,}3;\ 31{,}15)$ and $(61{,}7;\ 31{,}65)$. Therefore, the measurement errors of the complex dielectric permeability may place in ranges of values from $-0{,}45$ up to $+0{,}05$ for the real and from $-0{,}5$ up to 0 for the imaginary parts in the first case and in the second case - from $-0{,}05$ up to $+0{,}45$ for the real and from 0 up to $+0{,}5$ for the imaginary parts (true value is $\dot{\varepsilon} = 61{,}5 + j31{,}4$).

The scattering parameters measurement error effect is shown at fig. 8, 9, where the level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$calculated for cases of measurement

$Re(S_{11})$, $Im(S_{11})$, $Re(S_{21})$, $Im(S_{21})$ with the maximal values of the basic error -1% and $+1\%$ are submitted. From the diagrams follows, that the minimum point was displaced to value $\dot{\varepsilon} = (60{,}8 \pm 0{,}4) + j(31{,}4 \pm 0{,}4)$ in the first case and to value $\dot{\varepsilon} = (62{,}2 \pm 0{,}4) + j(31{,}4 \pm 0{,}4)$ - in the second. Thus the goal function maximum has value $U(\dot{\varepsilon}) = 2 \times 10^{-5}$.

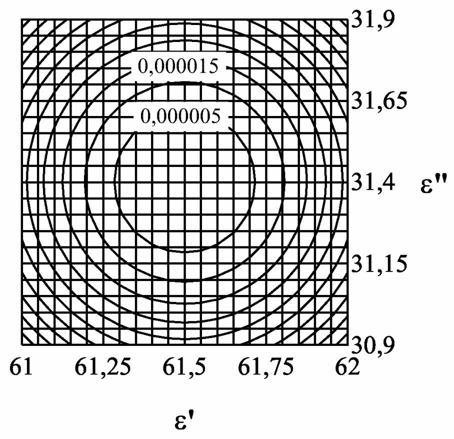

Fig. 4. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at one frequency point $\Delta = 1{,}5$

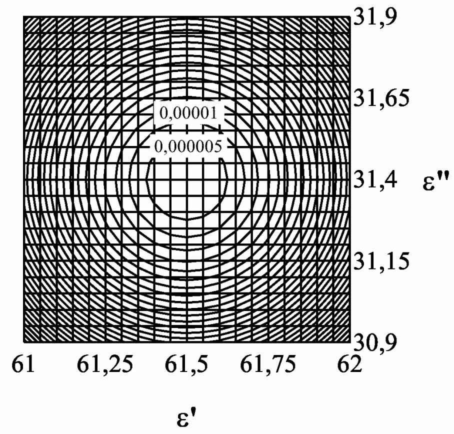

Fig. 5. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at three frequency point frequency points $\Delta = 1{,}3;\ 1{,}5;\ 1{,}7$

The numerical results of studying of the waveguide sensor manufacturing accuracy effect on the complex dielectric permeability measurement error are submitted on fig. 10. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ are represented for the case when as experimental reflection and transmission coefficients the values calculated for the testing waveguide sensor, internal radius of which is $r_1 = 0{,}55$ mm that corresponds to the manufacturing error 0,05 mm, are used: $\mathrm{Re}(S_{11ms}) = -0{,}6242052495$; $\mathrm{Im}(S_{11ms}) = 0{,}0801348545$; $\mathrm{Re}(S_{21ms}) = 0{,}3741141709$; $\mathrm{Im}(S_{21ms}) = 0{,}0833166601$.

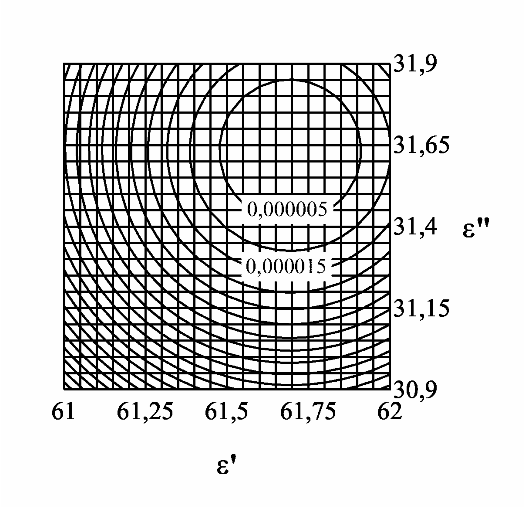

Fig. 6. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}4955$

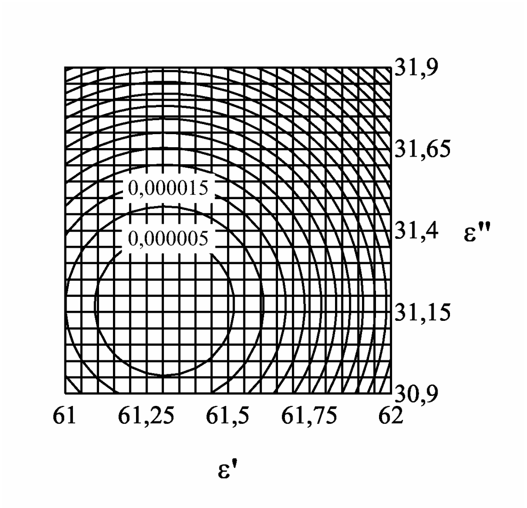

Fig. 7. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}5045$

From the diagram (fig. 10) follows, that the goal function minimum was displaced to a point $\dot{\varepsilon} = 73 + j35$. The measured value of the complex dielectric permeability differs from true ($\dot{\varepsilon} = 61{,}5 + j31{,}4$) on value $10{,}5$ for the real part and $3{,}6$ for imaginary. This error value is much higher, than in the cases have been considered above, therefore for it reduction it is necessary to accept the following actions:

to optimize the waveguide sensor geometrical sizes for the specific types of measurements;

to execute the exact measurements of the waveguide sensor tube geometrical sizes after its manufacturing;

before measurements to use the actual geometrical sizes of the waveguide sensor tube as parameters of the mathematical model and to improve its values by the testing measurements of the complex dielectric permeability of the material with known parameters.

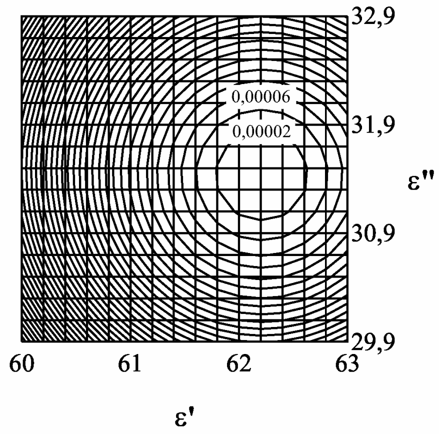

Fig. 8. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}5$ at the measurement error of the scattering parameters values -1%

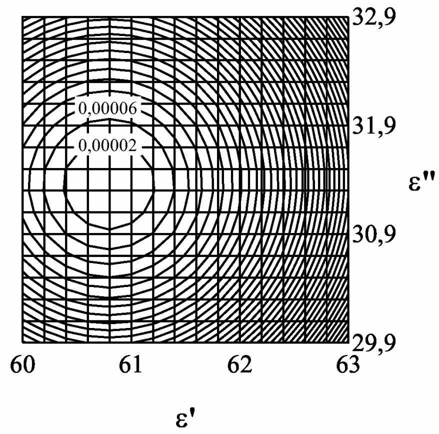

Fig. 9. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}5$ at the measurement error of the scattering parameters values $+1\%$

Conclusion. The measurement method of the complex dielectric permeability materials at microwave range, using the exact solution of the boundary electrodynamical problem of the electromagnetic waves diffraction at the waveguide sensor as a dielectric tube, which is placed in parallel of the rectangular waveguide narrow walls, is developed.

The software for calculation of the materials complex dielectric permeability by the measurement results of the scattering parameters at the waveguide sensor containing a sample of the tested material is developed.

The numerical studies by definition of the calculations efficiency and accuracy with using the test waveguide sensor of 3 sm wavelengths range which have shown stability of computing procedures work and a possibility of the dielectric permeability measurement of materials with high accuracy are executed.

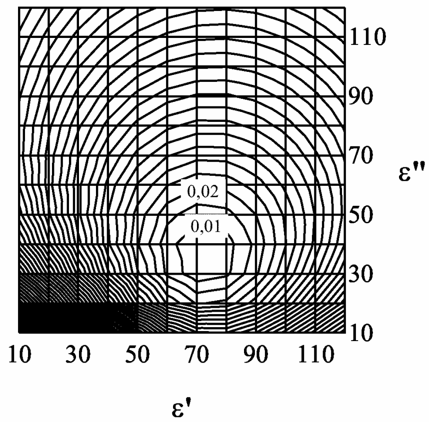

Fig. 10. The level lines of the goal function $U(\dot{\varepsilon}) = U(\varepsilon', \varepsilon'')$ for the test waveguide sensor at frequency $\Delta = 1{,}5$ at the manufacturing error of the tube internal radius $+0{,}05$ of mm

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