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ELECTROPHYSICS, ELECTRON AND ION BEAMS, PHYSICS OF ACCELERATORS

Computerization of Experiments on Interaction of Microwave Electromagnetic Radiation with Heterogeneous Liquids

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Abstract—A method for computerization of experiments on the interaction of microwave electromagnetic radiation and heterogeneous liquids is implemented as a measurement software complex that is integrated in the laboratory setup. The complex allows computerized measurements of various parameters of interaction of electromagnetic waves and material substances, control of the setup, and off-line processing of experimental data. The proposed computerized experimental procedures are superior to conventional manual procedures owing to faster and simpler measurements and analysis. The advantages of the proposed complex are demonstrated in experiments with known substances and artificial colloids and emulsions that contain magnetite nanoparticles.

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INTRODUCTION

Recent progress in measurement and information technologies makes it possible to substantially improve experimental procedures and the methods for data analysis [1–4].

The interest in the study of interaction of electromagnetic fields with heterogeneous liquids, in particular, colloids and emulsions, has been driven mainly by practical applications of artificial colloids and emulsions and the fact that such structured systems are widely spread in nature [5–7]. Note an important problem related to the remote control of the physicochemical properties of such systems using microwave radiation. Evidently, the analysis of electrophysical parameters of colloids and emulsions (microwave reflection and transmission coefficients and permittivity) is needed for the efficient control of the physicochemical properties with the aid of microwave radiation.

The purpose of this work is the development of a measurement software complex that allows computerized experimental study of electrophysical parameters in the microwave range. In addition, the measurement complex must be equipped with a software unit for the calculation of the needed parameters of colloids and emulsions, in particular, permittivity. One of the main advantages of the software complex is significant acceleration of the data acquisition and analysis in comparison with conventional manual procedures.

The setup consists of an Agilent Technologies ENA-L E5062A network analyzer, connection cables, a specific coaxial measurement cell [8], a PC that is interfaced with the experimental device using GPIB bus, and original software. Figure 1 demonstrates the block diagram of the setup. Coaxial measurement cell *4* represents a two-port with scattering matrix parameters S_{11}, S_{21}, S_{22}, and S_{12} that must be measured.

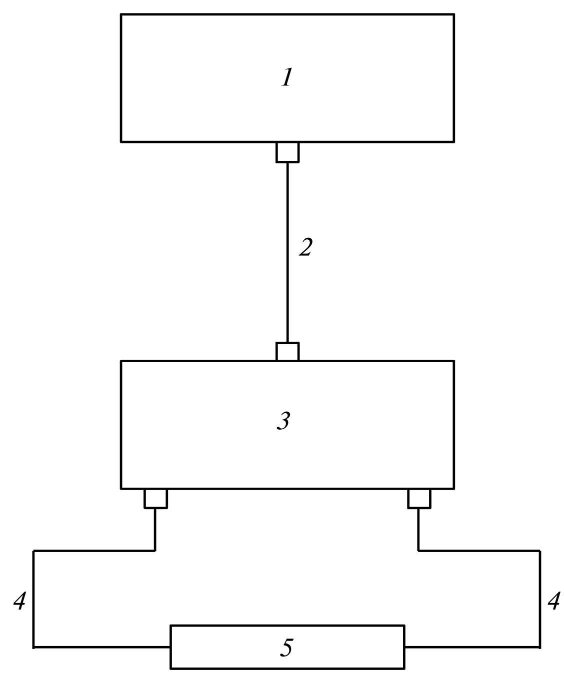

Fig. 1. Block diagram of the setup: (*1*) PC, (*2*) digital analyzer of microwave circuits, (*3*) flexible coaxial connection cable with an impedance of 50 Ω, and (*4*) coaxial measurement cell with the substance under study.

Parameters S_{11} and S_{22} characterize the reflection of electromagnetic waves from the cell. Parameters S_{12} and S_{21} characterize the properties of electromagnetic waves having passed through the coaxial cell.

A National Instruments G programming language and LabView 2011 software [9] are employed in the development of the software complex.

The complex can be conditionally divided into three complementary components (measurement, computation, and analytical). The functionality of the complex is determined by the problems under study and can be modified with allowance for experimental tasks and problems of mathematical analysis.

1. MEASUREMENT COMPONENT OF THE SOFTWARE COMPLEX

The main functions of the first part of the complex are as follows:

(i) interface of the PC and measurement device with tuning of the needed measurement parameters (selection of the needed quantity, direction of measurements, number of experimental points, etc.);

(ii) readout of experimental data from the measurement device with predetermined parameters and manual readout with the selection of settings;

(iii) data writing in an ANSI text file in a folder whose name contains the name of the measured parameter, name of the sample, and measurement time.

The acceleration of the measurement procedure is related to requirements on preliminary tuning of the experimental setup prior to each experimental session and sequential readout of the measured parameters of one sample using conventional software using which the PC is interfaced with the device.

National Instruments development drivers [10, 11] serve as the low-level software with which the PC is interfaced with the measurement device via a GPIB bus.

The drivers make it possible to tune all of the parameters of the Agilent Technologies ENA-L RFE5062A network analyzer, control the measurements, and read experimental data from computer memory.

An advantage of the complex lies in the fact that the software can be tuned with minimum variations in the original code using substitution of the drivers when a different device must be used in experiments.

The measurement part of the software complex allows both manual and automatic measurements. In the first regime, the type of the measured parameter, direction of measurements, and the remaining parameters can be tuned. The second regime is efficient in multiple similar measurements with the further processing of experimental data in the computation part of the complex. Default parameters are selected for the measurement of scattering matrix parameters S_{11} and S_{21} in one direction and data storage in a text file with the corresponding format. The automatic measurement regime is also used for simplification of experimental study aimed at the synthesis of new materials rather than the analysis of material properties in the microwave range, which is only used to additionally characterize the samples. In this case, the manual tuning is unnecessary. The advantages of the automatic regime show that students can use it for laboratory works and study.

2. COMPUTATION COMPONENT OF THE SOFTWARE COMPLEX

The second part of the complex is used for processing of internal and external experimental data. The main functions of the component are as follows:

(i) reading of experimental data from the file;

(ii) tuning of the geometrical parameters of the measurement cell that affect the calculations with the further graphical representation of a model of the cell;

(iii) recalculation (using enumeration and coordinate descent built-in algorithms) of the measured or prerecorded frequency dependence of the scattering matrix parameters of the sample that represents a part of a layered structure in the coaxial cell into the frequency dependences of the real and imaginary parts of permittivity and data writing in a text file.

As distinct from the measurement component, the computation component is not related to a specific model of the measurement device that is used for data acquisition. Note that a predetermined format of the data file is used. Figure 2 shows a screenshot of the working window of the computation component.

The measurement cell with the sample under study represents a layered structure (Fig. 3).

The quantities that are needed for computations are parameters of the scattering matrix of the four-port S parameters. For a layered structured, the parameters are represented as [11, 12]

$$S_{11} = \frac{Z_{\text{in}}^{(n)} - Z_{(n+1)}}{Z_{\text{in}}^{(n)} + Z_{(n+1)}},$$

$$S_{21} = \prod_{j=1}^{n} \frac{(Z_{\text{in}}^{(j)} + Z_j)}{Z_{\text{in}}^{(j)} + Z_{j+1}} e^{i\phi_j},$$

where $Z_{\text{in}}^{(n)}$ is the input impedance of the structure given by

$$Z_{\text{in}}^{(n)} = \frac{Z_{\text{in}}^{(n-1)} - iZ_n \tan(k_{nz}d)}{Z_n - iZ_{\text{in}}^{(n-1)} \tan(k_{nz}d)} Z_n.$$

The real and imaginary parts of the complex permittivity can be represented in terms of parameter S_{11} or S_{21}. The accuracy is higher when parameter S_{21} is used, since the measurement error of the transmission coefficient is normally less than the error of the reflection coefficient [13].

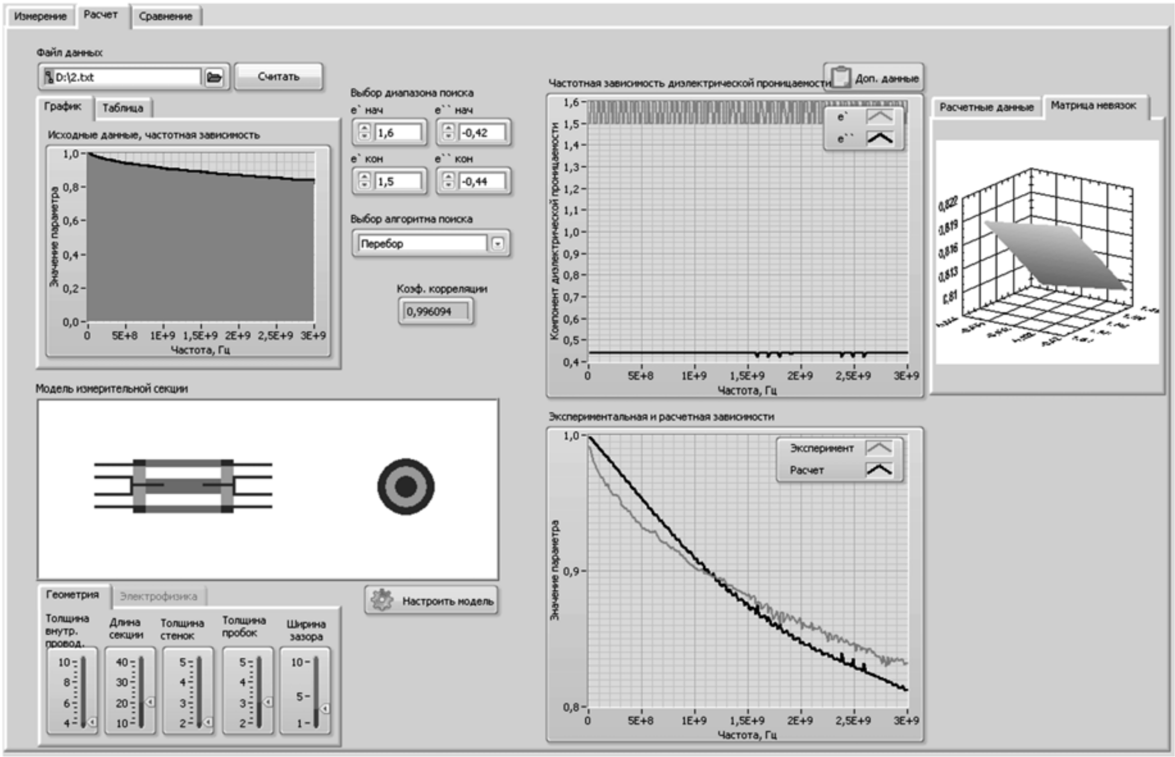

Fig. 2. Screenshot of the working window of the computation component.

The permittivity is not explicitly represented with the aid of the above formulas. Therefore, mathematical methods must be employed to find a minimum of objective function (difference between the measured and calculated values) [14]. Note a possibility of incorrect solutions owing to periodic dependences of parameters S_{11} and S_{21} on permittivity. Therefore, an initial approximation that is close to the true value of permittivity must be chosen for the minimization procedure. The minimum permittivity may serve as the initial approximation at relatively low frequencies when the length of the sample is less than one quarter of a wavelength.

A search algorithm involves enumeration of all possible combinations of the real and imaginary parts of complex permittivity with a certain accuracy in the given interval. In the coordinate descent procedure [15], we search for certain values that are substituted in the expressions for S_{11} and S_{21}. The difference between experimental and calculated values of the scattering matrix parameters is found as the distance between two vectors that must be minimized. The accuracy increases when the algorithm involves a feedback that employs a floating interval in a search for the values. The Pearson correlation coefficient, which is used in statistics for estimation of correlation dependence, serves as the parameter for accuracy estimation. The coefficient is determined as a ratio of the expected product of deviations of random quantities from mean values to the product of variances of these quantities [16, 17]:

$$r_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sigma_x\sigma_y}.$$

If the absolute value of the correlation coefficient is unity (zero), the random quantities are linearly dependent (independent). Intermediate values correspond to degrees of correlation.

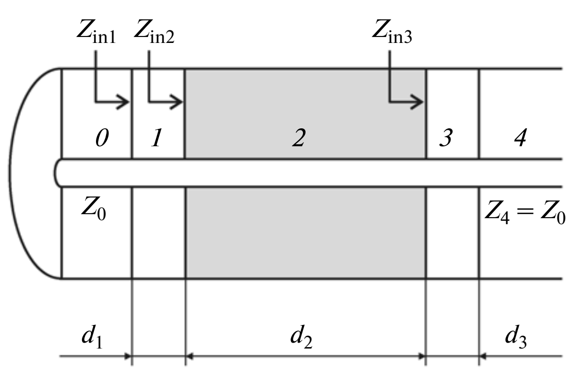

Fig. 3. Schematic representation of the layered structure under study: (Z_{in}) input impedance of the layer, (Z) impedance of the layer, (d) layer thickness, (*0*) and (*4*) air, (*1*) and (*3*) plugs made of a weakly absorbing material, and (*2*) substance under study.

The algorithm for the minimization of the objective function yields complex permittivities of the sample under study at several frequencies. These values are used to calculate the parameters of the scattering matrix of the layered structure. Then, the correlation of the experimental and calculated parameters is verified. The maximum possible correlation coefficient is reached using a variation in the limits of the search interval.

Thus, the computation algorithm represents two-stage optimization, first, in the space of complex permittivity and, then, in the space of the limits of the starting search interval.

The efficiency increases when the computations are performed at all of the informative points with a corresponding increase in the computation time. The imported data are represented as plots or tables depending on the specific option of the menu. A model of the measurement cell must be tuned prior to the measurements using variations in geometrical configuration (diameter of the internal conductor, gap width, cell length, and thickness of plugs) and electrophysical parameters (plug material and material of waveguide section). The image of the cell is automatically updated on the real scale. Control windows make it possible to input the range for permittivity search. Variations in the input data make it possible to reach the maximum correlation of the experimental and calculated curves of coefficient S_{21} versus frequency. The calculated dependences of the imaginary and real parts of permittivity are separately plotted. In addition, the imaginary and real parts of permittivity are tabulated and the matrix of residuals at a certain frequency is separately represented on a 3D plot. An additional option allows the selection of algorithm (enumeration of all possible values in the given interval with the predetermined accuracy or coordinate search).

3. ANALYTICAL COMPONENT OF THE SOFTWARE COMPLEX

The third part of the software complex makes it possible to perform comparative analysis of up to six curves that are plotted after data reading from the corresponding text files. The analysis of the measured or calculated data often involves representation of the frequency dependences of different samples on one plot. Such a representation allows a comparative analysis based on the regularities of the positions of the curves. The software complex is portable if a LabView Run-Time Engine package is installed (i.e., the operation is started using an *.exe file). When the LabView Run-Time Engine package is not installed, the complex can be ported as a setup file that contains the original code and the needed resources.

4. APPLICATION OF THE SOFTWARE COMPLEX

The software complex makes it possible to computerize the measurements of electrophysical parameters that characterize the interaction of electromagnetic waves with various substances, including the measurements of the reflection and transmission coefficients of the electromagnetic wave and the standing-wave ratio and to calculate the permittivity. The permittivities of several substances (water, kerosene, ethanol, and glycerin) that are calculated using the software complex coincide with the known permittivities of these substances. This circumstance proves the efficiency of the complex. The complex was used for the study of the characteristics of microwave radiation in the experiments in which the coaxial cell was filled with various colloid solutions and emulsions (burning kerosene (GOST 11128-65), preliminary purified oil from the oilfield in the Leningrad oblast, colloid solution of magnetite nanoparticles dispersed in burning kerosene, and emulsion that contains magnetite nanoparticles and water microdroplets in kerosene). The frequency dependence of the microwave power absorption coefficient was studied in [18]. The experimental results show that the software complex allows the analysis of colloid and emulsion systems with close permittivities and makes it possible to detect magnetite nanoparticles in solution. Thus, the software can be used for the experimental study of the properties of colloids and emulsions at frequencies of up to 3 GHz. Acceleration of the data acquisition and analysis and the selection and tuning of the electrophysical parameters are the advantages of the complex. The last advantage is related to the flexibility of the complex, since the software can be tuned with allowance for specific tasks and problems of experimental study. The flexibility of the software complex allows applications in education (laboratory and practical works) of specialists, bachelors, and masters students at natural science faculties in the framework of the specialties of Physics, Radio Physics, Material Science and Technology, and Electronics and Nanoelectronics (Micro- and Nanoelectronics and Diagnostics of Nano- and Biomedical Systems). The software complex is being used for preparation of several diploma works and PhD theses. The novelty of the complex in comparison with similar systems (e.g., Agilent Technologies products) is related to a combination of the measurement, computation, and analytical components; flexibility of the procedures for data acquisition, processing, and analysis; and possibilities for application of hardware from different companies using the corresponding drivers of the devices.

CONCLUSIONS

A variant of computerization of experiments on the interaction of electromagnetic waves and heterogeneous liquids has been presented. The method is implemented as a measurement software complex [19] that is integrated in a setup for the study of electrophysical parameters of liquids in the microwave range. The complex makes it possible to automatically perform detailed study of several parameters of electromagnetic waves that interact with a substance and allows remote control of the measurement equipment and processing of experimental data.

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