An automated measuring complex of electromagnetic parameters of materials in the field of superhigh frequencies

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Abstract. This work is dedicated to the features of measuring the electromagnetic parameters of materials. In the field of superhigh frequencies, there are practically no documents regulating the requirements for the properties of materials and means for measuring the electromagnetic parameters of materials. To solve the problems of metrological support for this frequency range and new materials, several steps are required. One of them is the development of a measuring complex. This work describes the composition of the developed model of such a complex and its distinctive features. The text contains models of materials. The extended frequency range from 200 MHz to 80 GHz. The range of external magnetic fields has been expanded from 4 kA/m to 70 kA/m.

1. Introduction

Measurements of parameters of dielectric materials and products are widely used in solving various problems in both industry and scientific research. The most important of them are:

- Controlling the quality and availability of products, for example, when creating dielectric substrates and electrical insulation materials;
- Implementing Express-analysis on production lines of chemical plants;
- Studying the properties and structure of substances in the creation of new radio engineering and electrical insulation materials with specified properties;
- Researching biological systems;
- Measuring molecular and atomic constants.

Dielkometry methods are widely used due to their high sensitivity, versatility in selecting the research object, and applicability for measurements in a wide range of frequencies, temperatures, pressures, and other influencing factors.

Also of interest to the industry is the measurement of parameters of magnetic materials.

In this regard, a large selection of measuring instruments for electromagnetic parameters of substances and materials has been created. Further development of electronics, electrical engineering, and communication means leads to the need for its growth and improvement, and requires increasing the accuracy of measurements.
In solving the problem of metrological support of the existing selection of measuring instruments in this field of measurement of dielectrics and magnetic materials, an important role is played by standard samples of relative permittivity and magnetic properties, which allow for complex verification of measuring instruments, their calibration, testing and have undoubtedly advantages of a relatively simple organization of the state supervision service and ensuring the uniformity of measurements of electromagnetic parameters.

Standard samples of relative permittivity and magnetic properties are standard samples of the property. They are measured in the form of a substance with a physical value established during certification. This value characterizes this property. Standard samples are intended for:

- calibration, certification and verification of measuring instruments of relative dielectric permittivity;
- metrological certification of measurement methods;
- monitoring the accuracy of measurement results.

We will give a brief description of measuring instruments for dielectric parameters of substances and materials, which determines both the nomenclature of standard samples and their metrological characteristics.

The existing selection of measuring instruments consists of specialized devices - dielmeters intended only for measuring the relative permittivity ($\varepsilon$) and the tangent of the dielectric loss angle (tg$\delta$) of substances and materials in various aggregate states, as well as non-specialized equipment, which includes electro- and radio-measuring devices used in conjunction with measuring cells. In the latter case, the determination of $\varepsilon$ and tg$\delta$, as well as the magnetic properties of substances and materials, is carried out through the measured parameters of the circuits and signals. The design of the measuring cells is determined by the frequency range in which the measurements are made, the aggregate state of the test substance, the method of influence on the substance, etc. The measuring cell as part of the measuring circuit is either a capacitor (at low and high frequencies), or a resonant and quasi-resonant system (in the microwave region). For measuring magnetic properties at low and high frequencies, the measuring cell is an inductor.

After analysing the market of measuring instruments, it follows that the devices mainly have the following technical characteristics:

- the range of measured values $\varepsilon$ for liquid and solid materials is from 1 to 5000 – up to 0.02 %;
- the range of measured values of tg$\delta$ is from 5·10^{-5} to 5 – up to 15 %;
- residual magnetic induction $B_r$ from 0.1 to 2500 TL – up to 2%;
- residual magnetization $M_r$ - from 0.9 to 2000 kA/m – up to 2%;
- coercive force $H_{cM}$-from 0.1 to 4000 kA/m – up to 2%;
- relative magnetic permeability - from 1 to 10000 – up to 5%.

The existing variety of methods and means for measuring electromagnetic parameters of materials is determined by wide frequency limits of applicability, the need to measure the parameters of substances and materials of various aggregate states in a range of temperatures, pressures and other air influences, which creates certain difficulties in solving the problem of metrological support of this area. This is particularly true for non-specialized equipment. The measurement error is due to the instrumental error of the selected circuit parameter meter and a number of errors related to the design features of the measuring cells and their inclusion in the measuring circuit.

The main problem area is the area of ultrahigh frequencies for measuring the electromagnetic parameters of magnetic materials, in particular for ferrites. Most standards have applications for soft magnetic materials with a coercive force of up to 4 kA/m and at frequencies up to 200 MHz. These standards are not applicable for ferrites. The current needs of the industry require an expansion of the frequency range to several tens of gigahertz and an increase in the measuring range of the coercive force to 50 kA/m, as well as the use of new materials.

2. Measuring complex
To achieve this goal, the first step was to develop an automated measuring complex of electromagnetic parameters of solid materials in the frequency range from 8 GHz to 80 GHz. The layout of the complex
includes a set of measuring cells, a panoramic meter standing wave ratio voltage and attenuation; a panoramic type indicator YA2R-67, a harmonic signal generator type G4-141, attenuators, thermistor power meter type M3-22A, power supply type APS-7612L; electromagnet with a field of up to 75 kA/m; magnetic field meter type ЭМ2-14; interface devices such as the Elvis II laboratory station and a personal computer with specialized software [1].

The frequency response meter allows you to measure the dependence of the power transmission or reflection coefficients on the frequency of an electromagnetic oscillation. To make measurements, the device must be connected to a waveguide path consisting of a set of directional couplers equipped with detector sections, a waveguide section with the test object and a matched load. The device can operate in two modes: in the "overview" mode and in the "documentation" mode. In the review mode, the device performs periodic (80 ms, 1 s; 10 s) formation of a frequency-tunable oscillation and measurement of the power level in the waveguide path with the object under study. The measured frequency response is displayed on the indicator screen.

During operation, low-frequency signals are generated on a special connector of the indicator, designed to control the analogy recorder. These signals are replaced with similar ones from the interface device. The main requirement for the interface device is the possibility of synchronous two-channel digitization of analogy signals coming from the ICH, and compatibility with a personal computer for data transmission.

Special software is required for the interaction of the frequency response meter and the interface device with a personal computer. For the Elvis II station, such software was compiled in the LabVIEW environment, and software development for computer automation of the physical experiment was carried out in the same environment. The interface device is designed for synchronous measurement, digitization, and transmission to a computer of signals coming from EM2-14 and M3-22A devices and carrying information about the power of electromagnetic vibrations and magnetic field strength.

Attenuators are used for decoupling the main parts of the waveguide path: due to the high level of attenuation (about 10÷15 dB), they can suppress the energy of electromagnetic waves reflected from inhomogeneities of the waveguide path. In particular, the first attenuator extinguishes the wave reflected from the plate of the test material to the generator, the second – the wave reflected from the head of the thermistor power meter.

The DC power supply is designed to adjust the current in the electromagnet winding. The unit uses a remote-controlled power supply that allows you to smoothly adjust the output voltage between 0 and 60 V in 10 mV increments.

The electromagnet is designed to create a permanent magnetic field that affects the electrodynamic parameters of the material under study.

This complex has several features.

The first feature is the presence of a controlled electromagnet. Currently, there are no measurement systems on the market that can control the external magnetic field in a wide range. In most cases, all measurements are made with a natural magnetic field.

The second feature is the presence of a theory. The theory refers to the use of mathematical and computer models to calculate characteristics for different materials for different measuring cells. This makes it possible to conduct virtual experiments.

The third feature is a consequence of the first two due to the integration of experiment and theory. The researcher conducting the experiment receives a complete picture as a field and frequency portrait of electromagnetic materials in the specified frequency and field ranges. One of the measured magnetic properties is the texture of the material.

Testing and verification of the complex was carried out on samples of magnetic materials from «Ferrite-Domain».

3. Material model
The complex has several models. Some models describe the material, while others describe the electrodynamic problem for different measuring cells.

3.1. An approximate theory of ferromagnetic resonance in a hexaferrite polycrystalline material
Based on the materials of the dissertation "Experimentally corrected computer models of hexaferrite gyromagnetic resonators" by P. S. Kolodin [4], we can distinguish a type of classical model in the form of an approximate theory of ferromagnetic resonance in a hexaferrite polycrystalline material. This theory differs from many other models in that it takes into account the texture of the material.

At temperatures below the critical level (Curie point), ferrites are magnetically ordered materials; in the vast majority of cases, and their magnetic structure is ferrimagnetic. The model proposed by L. Neel is widely used to describe such a magnetic structure. According to this model, the magnetic moments of ferrimagnets' atoms (first of all, the spin magnetic moments of the electrons of unfilled electron shells) form, as in antiferromagnets, two sublattices with the magnetizations \( \mathbf{M}_1 \) and \( \mathbf{M}_2 \) opposite to each other. The reason for the formation of magnetic sublattices is the exchange interaction, which orders the electron's own mechanical (spin) moments. Since, as is known, the intrinsic mechanical moment of an electron is related to its magnetic moment, the exchange interaction leads to the ordering of atomic magnetic moments. At the same time, since the sublattices are formed by atoms of different chemical elements, the vectors \( \mathbf{M}_1 \) and \( \mathbf{M}_2 \) differ from each other not only in direction, but also in modulus. Because of this, the total magnetic moment of a ferrimagnet, in contrast to an antiferromagnet, is not zero; hence the origin of the term "uncompensated antiferromagnet", often used in relation to the magnetic structure of ferrites.

Based on such a model, we can conclude that the magnetic state of the ferrite as a magnetic material is described by the vectors of the sublattices \( \mathbf{M}_1 \) and \( \mathbf{M}_2 \). In practice, however, the magnetic properties of the ferrites typically work for themselves with these vectors, and their combinations \( \mathbf{M} = \mathbf{M}_1 + \mathbf{M}_2 \) vector of ferromagnetism and the antiferromagnetism vector \( \mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2 \). At the same time, since the antiferromagnetic nature of ferrites (so-called the "opening" of sublattices) usually appears only in the long-wave part of the optical range, in the centimetre and millimetre wave ranges, the antiferromagnetism vector and sublattice structure are usually ignored and ferrites are described as ferromagnets characterized by \( \mathbf{M} \) magnetization.

Due to the fact that the vector \( \mathbf{M} \) is different from zero, the unit of volume of a ferrite crystal must be characterized by a magnetic moment, i.e. the ferrite crystal as a whole must have magnetization. However, numerous experimental data indicates that in the absence of an external magnetic field, a ferrite single crystal can have almost zero magnetization, i.e., it can be used as a magnetic field. being in a demagnetized state - a magnetic structure is formed in the crystal, in which the magnetization vectors of neighbouring domains form closed contours, reducing the total magnetic moment of a large-volume ferromagnet to almost zero. In a real sample of ferrite, just enough domains are formed and their magnetization vectors are oriented exactly so that the total energy of the ferromagnet is minimal.

The entire theory mentioned above fits well with classical models for ferromagnetic resonance in small ferrite particles or the model of a gyromagnetic resonator based on a single-domain single-crystal hexaferrite.

In the technique of ultrahigh and extremely high frequencies, gyromagnetic resonators based on hexaferrite polycrystalline materials are used. Polycrystalline material is a conglomerate of monocrystalline particles-grains (crystallites), which models were previously discussed. A characteristic feature of the granular structure of the material is that the particles in it are not identical to each other, but differ in shape, size, spatial orientation and other parameters.

A mathematical description of the granular structure of polycrystalline materials is usually carried out using the apparatus of probability theory and mathematical statistics: a material sample is considered as a collection of a large number of particles, whose various parameters (responsible for geometric dimensions, orientation in space, etc.) are analysed as random variables.

One of the most important characteristics of the granular structure of hexaferrite polycrystalline materials used in extremely high frequency devices is the texture quality. A polycrystalline material is called textured if it has an ordered spatial orientation of the crystallographic axes of particles.

The magnetic susceptibility tensor of a polycrystalline material \( \chi \) can be found by averaging the magnetic susceptibility tensors of particles over the ensemble. If the particles have the same size, the tensor \( \chi \) can be calculated using the formula:
\[ \dot{\chi} = \frac{1}{N_0} \sum \chi_k = \begin{pmatrix} \chi_\perp & i \chi_a & 0 \\ -i \chi_a & \chi_\perp & 0 \\ 0 & 0 & \chi_{||} \end{pmatrix}. \] (1)

In the case of a weak constant magnetic field strength and a good texture the material model is described by the tensor components using approximate formulas:

\[ \chi_\perp = A_1 \chi^{+} + \chi^{-} \] (2)

\[ \chi_a = A_2 \chi^{+} + \chi^{-} \] (3)

\[ \chi_{||} = A_3 \chi^{+} + \chi^{-} \] (4)

\[ \chi^{\pm} = \frac{H_{A_1} + H_0 + H_{A_2} \mp H_{A_3}}{2} \frac{M_s}{H_{A_1} + H_0} \] (5)

\[ H_n = a H_\omega \frac{H_{A_1} + H_{A_2}}{2} \frac{2}{H_{A_1} + H_0} \] (6)

where \( A_1, A_2, A_3 \) and \( K_\gamma \) are coefficients that depend on the texture quality and the intensity of the external constant field:

\[ A_1 = \frac{1 + \bar{X}^2}{2} + \frac{H_0}{H_{A_1} + H_0} (1 - \bar{X}^2) \] (7)

\[ A_2 = \bar{X} + \frac{H_0}{H_{A_1} + H_0} (1 - \bar{X}^2) \] (8)

\[ A_3 = \frac{H_0}{H_{A_1} + H_0} (1 - \bar{X}^2) \] (9)

\[ K_\gamma = \frac{1}{2 - \bar{X}} \] (10)

\[ \bar{X} = 2 \int_0^1 x p_x(x) dx, \] (11)

\[ \bar{X}^2 = 2 \int_0^1 x^2 p_x(x) dx. \] (12)

### 3.2. Oscillatory model

In addition to the classical approach, which attempts to describe a material and its properties through its internal structure and physical processes, there are also phenomenological models. These models do not profoundly affect physical processes and phenomena, their causes and laws of flow. They try to describe only the properties of interest in for this field of activity.

Consider a composite radio-absorbing material, which is a mixture of ferrite powders and a binder. A composite radio-absorbing material based on hexaferrite can contain up to 80% of ferrite particles. These particles can be of any size and shape [2]. The binding material is different dielectric materials. Particle shapes are considered arbitrary. The size of ferrite particles does not exceed 60 microns. The properties of the material are determined by the chemical composition, size, and shape of the ferrite particles. We consider the resonant field as a vector addition of the anisotropy fields and the shape field, taking into account the orientation of the particles. The vibrational model used for the study of such materials is approximate. It allows us to describe frequency-dependent processes occurring in such materials without going into the physics of the processes.

The electrodynamic properties of materials can be characterized through complex dielectric and magnetic permittivity. The dependence of the permittivity on the frequency in the range from 0.1 MHz to 100 GHz is almost constant. The resonances that the permittivity can experience are in the ranges of infrared and ultraviolet frequencies. The dielectric constant of a composite material, as well as the magnetic one, is represented as a complex value:

\[ \varepsilon = \varepsilon' - i \varepsilon'' \] (13)

\[ \mu = \mu' - i \mu'' \] (14)

where \( \mu_j, \mu_k \) is the partial magnetic permeability at the corresponding frequencies:
$$\mu' = 1 + \sum_{j=1}^{n} \mu_j \sqrt{1 + \left(\frac{f - f_{rj}}{\Delta f_j}\right)^2} \frac{\sin(\arctg\left(\frac{f - f_{rj}}{\Delta f_j}\right))}{\sqrt{1 + \left(\frac{f - f_{rj}}{\Delta f_j}\right)^2}}$$

(15)

$$\mu'' = \sum_{k=1}^{n} \mu_k \sqrt{1 + \left(\frac{f - f_{rk}}{\Delta f_k}\right)^2} \frac{\cos(\arctg\left(\frac{f - f_{rk}}{\Delta f_k}\right))}{\sqrt{1 + \left(\frac{f - f_{rk}}{\Delta f_k}\right)^2}},$$

(16)

$f$ – current frequency; $f_{rj}, f_{rk}$ – resonance frequency of hexaferrite powder in the mixture; $\Delta f_j, \Delta f_k$ – width of the resonance curve of partial magnetization.

In the vibrational model, the sum of terms is used for the imaginary and real parts of the magnetic permeability of composite materials. Each term corresponds to an expression for the input resistance of a parallel circuit with different values of the resonant frequency of detuning and partial magnetization. Due to the fact that this model is an adjustable model, all coefficients are selected experimentally.

Any functions that have a resonant character can be used as members of the sum [3]. In this way, we can apply the Gauss functions, which are mostly used in quantum mechanics to describe the radiation process.

3.3. A computer simulation model of a hexaferrite gyromagnetic material

Physical representations and mathematical models first formulated in the classical works of L. D. Landau and E. M. Lifshitz, C. Kittel, E. K. Stoner and E. P. Wolfart, M. T. Weiss, E. Schlem an, etc. and generalized later in the works of NIL GIR employees [4, 5] formed the basis for the development of a computer model of a hexaferrite gyromagnetic material. Computer implementation of these representations was carried out using the simulation method. This allowed us to create a model that generalizes the existing approximate theory of gyromagnetic resonance to the case of an arbitrarily oriented and arbitrarily magnetized material with an arbitrary texture quality.

The development of a new method for solving the static problem (the problem of the direction of the magnetization vector of a single-domain hexaferrite particle placed in an external magnetic field) led to the creation of such a model [4]. The method differs from its known analogues in that it allows us to obtain a solution for any of the two possible initial directions of the anisotropy field. Thus, if under specific conditions of the problem it is possible to have two stable solutions belonging to different (upper and lower) sections of the hysteresis loop, the new method allows finding both. For cases where the ambiguity of the solution is unacceptable, a method for choosing a solution based on information about the magnetic background of the particle was proposed [4].

The development of this method made it possible to significantly simplify the solution of the static problem and the calculation of the magnetization curves of hexaferrite polycrystalline material. By taking into account and tracking the magnetic background of each particle, the remagnetization curves calculated by the new method depend on the initial state of the material. By changing this state, it is possible to calculate not only the limit, but also arbitrary partial hysteresis loops.

Using the simulation method allowed us to create a computer model, the limits of applicability of which were wider than those of previously known models. The simulation computer model allows calculating tensor magnetic parameters and resonant characteristics of an arbitrarily oriented and arbitrarily magnetized material with an arbitrary texture quality.

4. Conclusion

As a result of this work, a model of an automated measuring complex of electromagnetic parameters of materials in the field of ultrahigh frequencies was developed. For this complex, new material models are used, allowing not only to conduct physical experiments automatically, but also to conduct virtual experiments. This complex widens the frequency range from 200 MHz to 80 GHz and the magnetic field range from 4 kA/m to 70 kA/m. In turn, this allows us to measure new materials that do not fall
under the current standards, taking the first step towards creating new standard samples, a relative
dielectric constant, and magnetic properties.

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