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EHF DIELECTROMETRY OF HIGHLY ABSORBING MEDIA. RADIATION SOURCE, THE INTERACTION REGION

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By means of computer simulation the measuring cell design of a dielectrometer developed before has been optimized. It was resulted in increased sensitivity and accuracy of measurements. The paper also deals with the performance requirements for the generator used in dielectrometer, and the choice of its stabilization mode is justified.

Keywords: *EHF DIELECTROMETRY, REFLECTION COEFFICIENT MODULE, MEASURING CELL, HIGHLY ABSORBING MEDIA.*

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1. INTRODUCTION

Study of the dielectric properties of substances is an important scientific and applied problem. Dielectrometry allows to obtain the information concerning the molecular structure and their symmetry [1], shape and geometric dimensions [2], water content in different materials [3] and structural changes occurred under the action of the external factors [4-6]. Investigation of the dielectric properties of biological materials is usually performed using the microwave dielectrometry, in particular EHF dielectrometry, which is a delicate tool for the water structure study. This is conditioned by the fact that molecules of water, which is the main component of biosystems, have dipole moment and rotational degree of freedom. Indeed, the most attractive in the dielectrometry of bio-objects is the high accuracy of the measurements in the real-time mode, which completely excludes the object failure that is an important factor while studying the functional properties of biosystems.

Hydration effects [7-9], complexation processes [6], conformational transitions of biopolymers and water state in biosystems of different organization levels [9-13] are studied by means of the EHF dielectrometry method. It is possible to judge the functional status of different organism systems in health and pathology [14-16] using the measured dielectrometric parameters of human blood.

Test experiments performed in clinical conditions to measure the dielectric characteristics of human blood and estimate the adrenal reactivity of erythrocytes [17] showed that the measurement complex based on the reflectometer [18] developed before requires an improvement. Measuring cell for biological objects loses the measurement stability if it is used sustainably (for 6-8 hours) and intensively, and while measuring the time dependences of the permittivity as well. It was found that for some peculiarities of the patient material the sensitivity of the measuring complex was not enough for the statistically reliable differentiation of the blood cell reaction on the action of biologically active substances.

The aim of the present work consists in the measuring cell improvement by means of computer simulation of the physical processes of interaction between electromagnetic waves and matter, in the requirements engineering to the radiation source performance and in the choice of a source stabilization technique used in dielectrometer.

2. PROBLEMS OF THE DIELECTROMETRY ACCURACY INCREASE OF HIGHLY ABSORBING MEDIA

In order to update the measuring cell, which is the part of the complex, we performed a set of numerical experiments concerning the optimization of the structure of the cell waveguide flanges and the choice of the optimal (from the point of view of the sensitivity and feasibility) substrate thicknesses, which confine the sample.

The software system developed in the mathematical physics department of IRE NASU [19] was used for the simulation. This software product allows to calculate and analyze the electromagnetic wave propagation in complex structures, which consist of an arbitrarily shaped dielectric with known values of the permittivity and conductivity. Computer experiments resulted in this paper were carried out by the finite-difference time-domain (FDTD) method. Here two-dimensional initial boundary problems for E-polarized field are considered. Characteristics of the time domain are converted to the frequency domain characteristics by the Fourier transformation [20].

In the experiment the cell was represented as the layered two-dimensional structure composed of the measured sample and the confining substrates placed in the waveguide shorted at one end and which completely fill its cross-section.

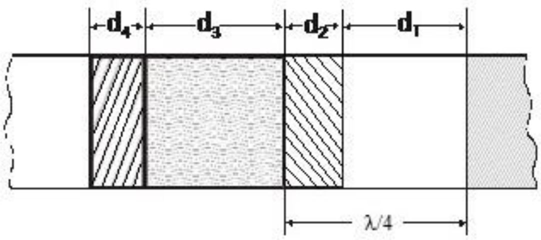

Fig. 1 *– Two-dimensional layered structure of the cell: d_1 is the thickness of an empty waveguide adjacent to the short circuitor; d_2, d_4 are the thicknesses of substrates confining the sample; d_3 is the sample thickness*

In the experiment the thicknesses of each layer were optimized. Water and aqueous solutions of ethyl alcohol with the ethanol mole fractions of χ_1 = 0,04 and χ_2 = 0,08 were used as the test substances. The values of the complex permittivity [21, 22], our measured experimental values [17] agree with, are known for these substances with adequate accuracy. Frequency dependence of the reflection coefficient from the optimized structure was calculated in the presence of the test substance. Used frequency band corresponds to the waveguide operating band and is represented as the wave number.

The choice of the confining substrate adjacent to the short circuitor was performed while optimizing. In the present cell this substrate is made of fluoroplastic and has the thickness equal to a quarter of the operating wavelength in the waveguide. The wave number corresponding to the operating frequency is equal to k = 827. As simulation showed (Fig. 2), the sensitivity can be increased one-half using a thinner substrate. In this case the absolute value of the reflection coefficient depends less on the operating frequency deviations. Decrease in the modulus of the reflection coefficient is also observed and this additionally improves the result since used four-point probe measuring line gives higher statistical confidence at these values.

Performed experimental measurements agree well with the calculated values and demonstrate the 1,5 fold increase in the sensitivity in modulus of the reflection coefficient.

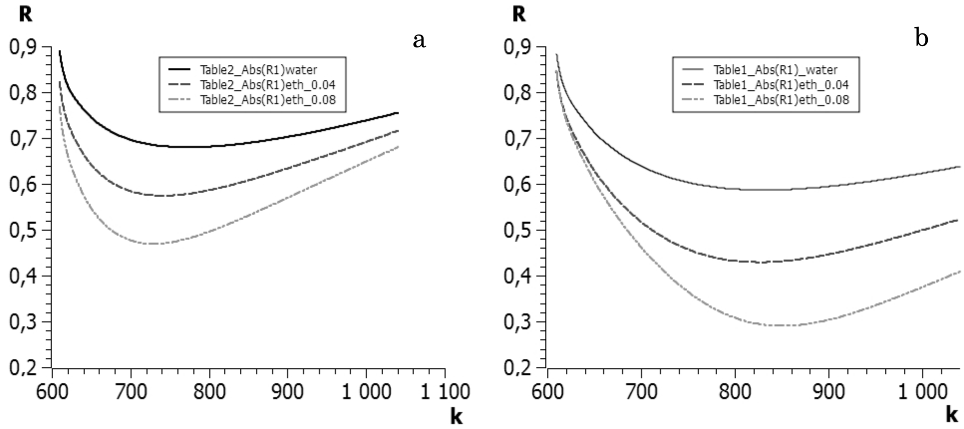

Fig. 2 *– Dependence of the modulus of the reflection coefficient (R) of the simulated cell on the wave number (k) at the thicknesses of the optimized substrate of* 1,4 *mm (a) and* 0,8 *mm (b) in the presence of the test substances in the structure*

Table 1 *– Experimental values of the modulus of the reflection coefficient*

Substrate thickness, mm	Distilled water	Ethanol solution with mole fraction of χ = 0,08
1,4	0,676 ± 0,003	0,537 ± 0,004
0,8	0,574 ± 0,003	0,357 ± 0,005

3. EHF RADIATION SOURCE REQUIREMENTS

In devices for measuring permittivity in highly absorbing media the following source requirements are identified: high short-term and long-term stability of the oscillator frequency, low supply voltage, reasonable dimensions and weight.

Use of the automatic frequency control (AFC) method with respect to the external high-resistance signal, which uses the frequency multiplier stabilized by the quartz resonator, is a rather difficult way to achieve the high stability. Moreover, with AFC-stabilization the source frequency noise is suppressed only in the capture range [23]. Frequency stabilization by external resonant system found a wide distribution due to the simplicity of its technical realization. The authors of [24, 25] proposed to use the quasi-optical concept of frequency stabilization circuits and capacity of solid-state oscillators, i.e., to use open resonators (OR) and Gunn diodes (GD) for these purposes. To provide a stable oscillation mode in the oscillating system it is necessary to support with high rarefaction of the natural frequency spectrum. In the limit it is necessary to approach to the single-frequency excitation mode of OR in the excitation band of the active element – GD. Besides, it is necessary to adjust the impedance of the non-linear element (a low resistance of the order of magnitude of some Ohms) and OR with the resistance approaching to that for free space.

The so-called sphere-angle-echelette OR where one of the mirrors consists of two echelettes placed at the blaze angle relative to the OR axis with the common vertex on the resonator axis is proposed. A detailed analysis of the electrodynamic properties of the sphere-angle-echelette OR [1] showed that in such resonators the grating is the additional selective element, and its properties are defined by the intersection of two resonance conditions:

– multiplicity of the resonator wavelength to a whole number of half-waves:

$$L = q\lambda/2, \tag{1}$$

where $q = 1, 2, 3,...$ is the longitudinal index of TEM-oscillations,

– autocollimation reflection.

In the case of rectangular echelette and its arrangement at an angle of autocollimation reflection $\varphi = 45°$ to the OR axis, the second condition can be expressed in terms of the echelette step height:

$$h = n\lambda/2, \tag{2}$$

where n is the number of the Floquet wave, in action $n = 1, 2, 3, 4, 5$.

Conditions (1) and (2) hold simultaneously on the non-dimensional frequency

$$K_r = nL/2h. \tag{3}$$

Mechanism of the formation of the quasi-fundamental oscillation field is studied in detail in [25]. In this paper we only note that this field shrinks to the resonator axis, and the diffraction losses of these oscillations are considerably less than for the fundamental oscillations. Since the field is shrinked to the resonator axis this fact can be the prerequisite for the decrease in the mirror aperture without significant increase in the diffraction losses and reduction of the Q-factor.

To design the Gunn oscillator on the given frequency the empirical formula for the step height was obtained based on the analysis of the angle-echelette OR model. Under the condition of the resonator excitation on the quasi-fundamental oscillation mode the echelette step height is chosen from the following relations:

$$h^H = 0{,}56\lambda \tag{4}$$

for the H-polarized wave, and

$$h^E = 0{,}48\lambda \tag{5}$$

for the E-polarized wave.

4. QUASI-OPTICAL OSCILLATOR WITH GUNN DIODES

For the automated dielectrometer operated at a fixed frequency of 39,5 GHz [18], which is in the free spectral range, the Gunn oscillator is developed. It is stabilized by the sphere-angle-echelette OR using the reactive-reflective resonator [23]. Cross-section of the investigated oscillator passing through the resonator axis and perpendicular to the echelette generatrices is shown in Fig. 3.

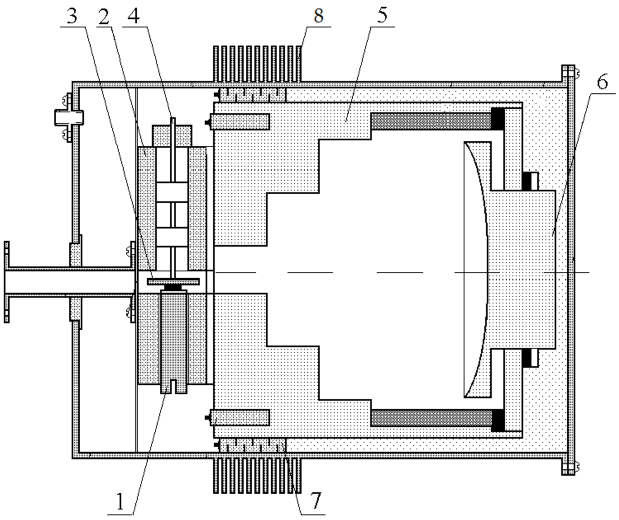

***Fig. 3** – Design of the quasi-optical solid-state oscillator*

Diode 1 is placed on the inset 2 with the waveguide cross-section of 7,2 × 3,4 mm. Body of the Gunn diode and disc 3 form the primary resonant circuit. Supply voltage is applied through the post 4 with high-frequency filter.

Small-sized quasi-optical sphere-angle-echelette OR is used in the present oscillator for the frequency stabilization. It is formed by the angle-echelette mirror 5 consisted of two stepwise deformed surfaces. This mirror is made as a single whole with the OR body to improve the mechanical hardness of the resonator. The second mirror 6 with the radius of curvature $R = 78$ mm forms a single whole with the moving mechanism, which is used for the resonator tuning on the required frequency. The mirror apertures are the same and equal to $a = 41$ mm (5,2 λ_{av}). The resonator length $L = 45$-46 mm was chosen from considerations of minimization of the mass and dimensions of the device, and it is not critical to the stability conditions. These conditions should hold for the equivalent OR with plane and spherical mirrors due to the fact that the studied OR is excited on the quasi-fundamental type, the field of which is shrinked to the resonator axis (diffraction losses are minimal). Body and echelettes of the OR are made of super-invar with the linear expansion coefficient $K = 2{,}61 \cdot 10^{-6}$ K^{-1} and the mirror 6 is made of copper with $K = 16{,}7 \cdot 10^{-6}$ K^{-1}. Adjusting screw of the mirror acts both as the tuning mechanism and the temperature compensator.

Oscillation frequency on the quasi-fundamental oscillation mode depends on the resonator length L, step height h and radius of curvature of the mirror R: $F_g = f(L, h, R)$. Frequency shift caused by the change in the resonator temperature is the function of linear expansion of the material α and refractive index of the filler ε: $\Delta F_g/\Delta T = f(\alpha, L, \varepsilon)$; here the change in the mirror curvature and step height is not taken into account.

For the purpose of improving the long-term stability of the radiation source the temperature stabilization system [25], in addition to the encapsulation one, is envisaged in the design. The value of the heat flow and its direction during the OR temperature stabilization is adjusted by two Peltier cell batteries 7 placed between the OR body and the external radiator 8 made of aluminum ($K = 209$).

Measurement of the oscillator characteristics was carried out using the standard equipment: frequency was measured by the heterodyne frequency meter Ch3-66, power was obtained by the measuring instrument M3-53 and generation spectrum was studied by the spectrum analyzer S4-28.

In Fig. 4 we present the frequency and the oscillator output depending on the resonator length L during OR tuning.

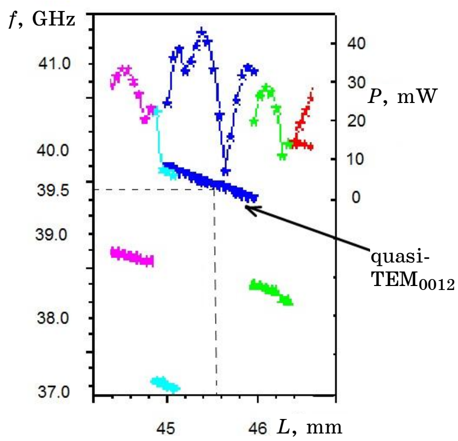

Fig. 4 *– Dependence of the frequency and the output power on the length of sphere-angle-echelette OR*

As seen from Fig. 4, generation has zone behavior. However, in contrast to oscillators with OR without additional dispersion elements (mirrors are smooth) [24], periodicity of generation zones is not observed here. The most pronounced zone is that where the excitation conditions of the quasi-fundamental mode hold (at the resonator length of $L = 45{,}5\text{-}45{,}4$ mm; $\lambda \sim 7{,}59$ mm; the longitudinal number is $q = 12$; quasi-fundamental TEM_{0012}). The relative frequency tuning in this zone is about 0,5%. Other generation zones where the radiation source is excited have unstable behavior.

In these conditions the long-term generation stability is provided by the stability of the OR geometric dimensions and matching circuits, and by the encapsulation of the whole unit as well. At different stabilization modes and with external temperature fluctuations the Peltier elements can operate as cooling and heating elements. In Fig. 5 we show the frequency deviation measured using the frequency meter Ch3-66.

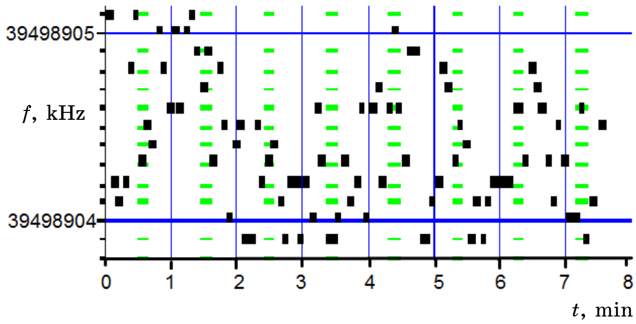

***Fig. 5** – Frequency deviation after temperature stabilization of the thermostat*

Main characteristics of the oscillator are the following: oscillation frequency F_g = 39,5 GHz; short-term frequency instability $\Delta F_g/F_g = 1{,}6\cdot10^{-8}$ measured per second; frequency noise level is not more than 105 dB/Hz at 20 kHz detuning; spectrum line width does not exceed 0,25 kHz; output power is 30 mW. Electronic retuning of the oscillator is about 8 MHz/V that implies about high Q-factor of the oscillating system and good agreement of a nonlinear element. Long-term instability estimated using the frequency measurements by heterodyne frequency meter is $\Delta F_g/F_g \sim 3\cdot10^{-7}$ and holds during the measurement time more than an hour under the active temperature thermostating $\Delta T \sim 0{,}1$ K for the oscillator temperature of 34 °C.

5. CONCLUSIONS

Thus, as a result the simulation of the measuring cell where the interaction between electromagnetic radiation and matter occurs is performed. The optimal sizes and widths of the dielectric substrates confining the cell volume are defined. Sensitivity and accuracy of dielectrometer are increased since the four-point probe measuring line used in dielectrometer gives better statistical confidence of measurements at the optimal parameters. It is shown that use of the quasi-optical temperature-controlled radiation source based on the Gunn diode improves the operational characteristics of dielectrometer. Frequency noise reduction of the oscillator allows to improve the signal-noise ratio and thereby to increase the sensitivity. Temperature stabilization of the source enables to reduce the time of putting into operation and perform measurements during 6-8 hours without constant errors conditioned by the frequency shift.

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