Automated system based on open resonator for measuring the electrophysical parameters of sheet dielectrics

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Abstract. In the article, the results of automation of the setup for measuring the dielectric permittivity of sheet dielectrics in an open resonator are presented. A program to control the positioning mechanism of the object under study, which allows setting the position of the sample with an accuracy of 6.25 μm in the longitudinal direction and 0.05625 ° in the angle, was written in the LabVIEW (National Instruments). For angular position of 30° of sheet dielectrics relative to the longitudinal axis of the open resonator resonance curves are experimentally obtained. Based on the data obtained, the calculation of the dielectric constant of the material is given.

1. Introduction
Today, a large number of various composite materials based on carbon fillers are being created: nanotubes [1] and highly dispersed carbon. For small material thicknesses, they have a high level of absorption of electromagnetic radiation.

When conducting scientific research on the electrophysical properties of materials using the quasi-optical resonator method, precise positioning of the object in the space between the mirrors is required. Manual adjustment of the position with the required accuracy when studying the properties of sheet dielectrics [2], medical threads [3], polymer filament [4] for 3D printers and semiconductor substrates [5] takes quite a long time. When conducting measurements, automation of the experiment is required, such works already exist in the non-destructive testing system: scanning systems [6], immersion control systems, various multifunctional complexes, clamps and technological equipment.

In this regard, it became necessary to create a hardware-software complex for measuring the parameters of sheet dielectrics in an open resonator.

2. Theory
Measurements of the dielectric constant of sheet material are based on the phenomenon of a change in the Q-factor of an open resonator when a sheet dielectric is introduced at an angle close to the Brewster angle. In this case, the location of the sample plane orthogonal to the electric field strength vector according to [7] leads to the least influence of the angle on the measured frequency shift.
When a dielectric sample is introduced into the antinode of the electric field of the fundamental mode of an open resonator (Fig. 1), formed by two spherical mirrors with a radius of concavity $R$, located at a distance $L$ from each other, the resonance curve is shifted and the bandwidth is broadened (Fig. 2).

The expression describing the connection of the $\delta f$ and the broadening of the resonance curve $2\Delta f_\perp$ with a thickness $d$, an $\phi$ angle and the dielectric constant of the $\varepsilon$ of a sheet dielectric is defined as:

$$\delta f_\perp = f_\perp - f_0 = -\frac{F_0 d}{\lambda_0} \frac{\varepsilon - 1}{\varepsilon \cos \phi} \left[ (\varepsilon - 1) \cos^2 \phi + 1 \right], \quad (1)$$

$$2\Delta f_\perp = \frac{F_0 \pi d^2}{\lambda_0^2} \left( \frac{\varepsilon^2 \cos^2 \phi - \varepsilon + \sin^2 \phi}{\varepsilon \cos \phi} \right)^2. \quad (2)$$

Where $F_0$ is the interspecies interval, and $\lambda_0 = c/f_0$. The “minus” sign here indicates that the flat dielectric introduced into the resonator shifts its frequency downwards.

In general, to estimate the complex permittivity of the fiber, it is necessary to solve the system of equations (1-2). However, for small losses in the samples, this system is divided into two independent equations. The real part of the permittivity determines the shift of the resonant frequency of the open resonator (1), and the imaginary part determines the broadening of the resonant curve (2).

3. Experimental part

The resonator method makes it possible to measure the parameters of sheet dielectrics with low losses. This method allows us to find the permittivity and thickness of sheet materials. The main advantage of this method is the multiple interaction of the electromagnetic wave with the sample. The open resonator is formed by two curved metal reflectors with a round aperture ($D = 80$ mm) and the same curvature ($R = 93.9$ mm), located at a distance of $L = 170$ mm. In the center of the reflectors there are communication elements in the form of narrow slits that communicate with external waveguide paths and ensure the polarization of the electric field in the resonator orthogonally to the slits. The sample is located in the center of the resonator (Figure 1) orthogonally to its axis and parallel to the electric field vector in its antinode. Figure 3 shows a block diagram of the measurement system.
Figure 3. Flowchart of the positioner of sheet dielectrics in an open resonator.

This positioner was integrated into a measuring system consisting of an open resonator, an Agilent vector circuit analyzer, and a personal computer (Figure 4). Figure 5 shows a fragment of the process for measuring the dielectric constant of a sample. The dielectric sample was fixed between the mirrors of the open resonator. To switch from the coaxial path to the waveguide one, a coaxial-waveguide transition was used.

Figure 4. Installation diagram for measuring the parameters of sheet dielectrics in an open resonator.

Figure 5. Dielectric constant measurement process.

To calculate the permittivity of a sheet dielectric in an open resonator, it is necessary to measure the thickness of the sample, determine the value of the interspecies interval, select the polarization of the radiation and the measurement angle, and then measure the shift of the resonant frequency or
the change in $Q$-factor. The permittivity was calculated according to the method «Measurement of dielectric constant of plane dielectrics using a quasi-optical open resonator» [8]. As a mechanical part of the system, a carriage with a helical transmission of movement along cylindrical guides was used. For the implementation of the electrical part of the system, the following components were selected: an Arduino Nano debugging board with an Atmega 328p microcontroller, 2 Nema stepper motors (17Hs08-1004S and 17HS401), a stepper motor driver (DRV8825) with 1/32 angle pitch splitting and A4988 with a whole step for longitudinal carriage movement, an optical limit switch, a DC power supply with a voltage of 12 volts. The system fasteners are 3D printed from acrylonitrile butadiene styrene plastic. Driver No 1 provides communication between the microcontroller and the stepper motor No 1, which is responsible for the horizontal movement of the test sample. The angular positioning of the object is carried out by the microcontroller via the stepper motor driver No 2.

The hardware management program is written in the LabVIEW graphical programming environment from National Instruments (Figure 6). In the "Moving the sample" window, the horizontal movement of the object is controlled with a minimum step of 6.25 micrometer with storing the position on the screen, and in the "Sample rotation" the angular movement of the object is performed clockwise and counterclockwise with a minimum step of 0.05625 °. It is also possible to calibrate the position of the sample and then move it to the center between the mirrors. In addition to the above, the dielectric constant can be calculated.

![Figure 6. Front panel of the control program](image)

4. Results

Based on the experimental values of the resonant frequency shift of an open resonator with a sheet dielectric for the main mode of oscillations $TEM_{0.0.38}$ using the formula (3) the value of the dielectric constant was calculated.

$$\varepsilon = \frac{1}{2} [A + \sqrt{A^2 + 4\tan^2 \varphi}]$$  \(\text{(3)}\)

where

$$A = 1 - \frac{\delta f \lambda_0 \sqrt{1 + \tan^2 \varphi}}{F_0 d} - \tan^2 \varphi.$$  \(\text{(4)}\)

Table 1 shows the results of the calculation of the dielectric constant.

| No | Name      | Thickness, mm | $f_{\text{res}}$, GHz | $\Delta f_{\text{res}}$, MHz | $\varepsilon'$, rel. unites |
|----|-----------|---------------|------------------------|-----------------------------|---------------------------|
| 1  | Plexiglass| 2.90          | 32.811                 | 374                         | 2.48                      |
As can see, when a dielectric is placed into the open resonator, the resonant frequency of the resonator shifts downward. For plexiglass it was 374 MHz, plastic 246 MHz and textolite 231 MHz. The dielectric constant of plexiglass was 2.48 rel. units, plastic 2.25 rel. units and 3.28 rel. units in textolite.

5. Conclusion
Thus, developed and tested automated system based on quasi-optical open resonator for measuring the dielectric parameters of sheet materials can be applied in industry for nondestructive control thickness of sheet polymer materials such as polyethylene films, plexiglass. The use of LabVIEW software as a control program allows the integration of the measuring system into a modern industrial equipment.

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