

## Extending the Functionality of Resonator Aperture Sensors for Microwave Diagnostics of Small-sized Objects

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The paper discusses the basic principles of functioning of resonator sensors with a movable probe-forming central conductor and approaches aimed at optimizing their measuring characteristics. The effectiveness of changing the coefficient of inclusion of an object in the electromagnetic field of the resonator is shown by introducing a mechanism into the sensor design that provides axial movement of the central conductor of the coaxial. This design allows the probing tip to be positioned both coplanar with the end aperture and displaced inside or outside the coaxial. It is shown that in order to diagnose objects with low dielectric losses, the probing tip must be pulled out of the coaxial, thereby transferring the probe to the mode of a monopole antenna. When the object has high dielectric losses, the required sensitivity of the sensor is achieved by shifting the probing tip into the inside of the coaxial, and the shortened capacitance mode is implemented.

Quantitative data are presented that characterize the operation of the tunable sensor within each of the two modes of operation considered, as well as convincing of the need to optimize the geometry of the resonator probe (RP) construct. The contribution of losses associated with the appearance of a wave field, the mismatch of propagation conditions in the volume of a resonant measuring transducer (RMT), as well as techniques aimed at eliminating their influence is shown. A comparative analysis of the use of conical and cylindrical probes as RMT is presented. It is shown that the shielding of samples makes much more sense for the use of a cylindrical construct in the diagnostics of objects with a low loss tangent. It is shown that it is possible to significantly reduce the influence of interfering factors caused by a change in the geometry of the sensor aperture assembly when the probe tip is moved, by using a hybrid signal  $(\delta Q/Q)/(\delta f/f)$ .

**Keywords:** Microwave diagnostics, Dielectric permittivity measurement, Open-ended coaxial probe, Tip-sample distance, Electromagnetic modeling.

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### 1. INTRODUCTION

Methods of microwave diagnostics are carried out by various approaches to solving theoretical problems, measurement techniques and designs of measuring transducers. According to the type of physical phenomena used in primary measuring transducers, microwave sensors can be divided into waveguide and resonator sensors [1, 2]. Resonator sensors (RS) have always been an alternative to waveguide sensors, mainly due to the higher sensitivity and hardware compactness of building diagnostic tools based on them. A higher sensitivity is determined by the accumulation of measurement information against the background of noise in  $Q$  (resonator quality factor) times. Hardware compactness is ensured by the combined method of extracting signals  $(\delta Q$  and  $\delta f)$  of measurement information and its versatility in a wide microwave operating range compared to waveguide ones. In turn, higher sensitivity makes it possible to use high-local applicators and not only measure the electrophysical parameters of the entire object, but also detect defects in near-surface layers. One of the main criteria for monitoring the objects under study in nanotechnology is the resolution of the diagnostic tools itself, both spatially and in terms of the measured physical quantity.

Local microwave diagnostics of various objects is aimed at determining such electrophysical parameters as  $\epsilon$  and  $\text{tg}\delta$ . As is known, in microwave sensors the range of materials under study is very wide [1-4]: from semiconductors and materials with superconductivity to

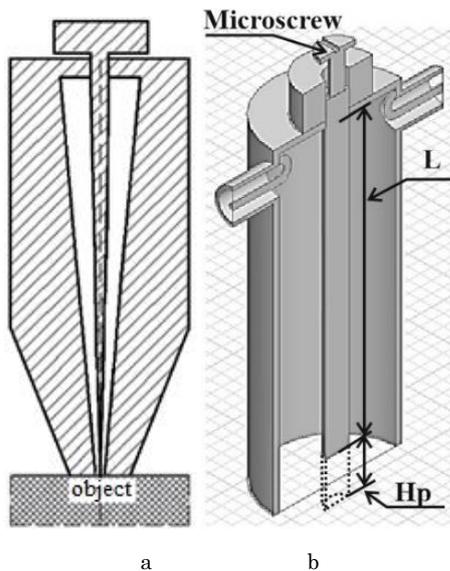
biological objects. Thus, for the diagnostics of materials,  $\epsilon$  and  $\text{tg}\delta$  of which vary in a wide range, sensors with different sensitivity and locality are required, which, in turn, are determined mainly by the geometrical parameters of the design of the RP aperture unit itself. To carry out express measurements, a universal sensor is required, the sensitivity and locality of which can be changed depending on the properties of the material under study. It becomes possible to achieve a significant change in the locality of the sensor without changing its structure by selecting applicators specially designed for diagnosing the areas of interest of the object with an area from several microns up to units of  $\text{cm}^2$  [5]. One of the ways to change the sensitivity of the RS quite widely can be to change the operating frequency of the resonator [5]. But, it is not always advisable to increase the frequency of operation of a coaxial resonant sensor by an order of magnitude or higher, due to the possible occurrence of higher types of oscillations [6, 7]. An alternative method for changing the sensitivity of a sensor based on a coaxial RP can be a change in the inclusion coefficient of the sample in the electromagnetic field of the resonator by changing the geometry of the RS aperture assembly.

The sensor studied in the work as a primary measuring transducer involves the use of a resonator coaxial probe with axial movement of the central probe-forming conductor relative to the end face of the coaxial. This technical feature of the design makes it possible to change the inclusion factor of the object in the resonator field [8], thereby providing the necessary measurement sensitivity.

The purpose of this work is to analyze the principle of performing measurements in a wide range of physical properties of various materials, as well as to analyze methods for optimizing the measuring characteristics of a coaxial resonator sensor, which is aimed at minimizing errors in diagnostics.

## 2. DESCRIPTION OF THE OBJECT AND RESEARCH METHODS.

The physics of the interaction of a coaxial quarter-wavelength resonator probe, the tip of which is in the plane of the aperture, with an object has already been sufficiently well studied [2, 8-10]. In such a design, radiation losses are minimal, because the field of wave nature is practically absent. The range of measured basic electrophysical parameters of such a sensor is within  $\varepsilon$ : 1-15  $\text{tg}\delta$ : 0.001-0.1. [11] To study objects of different consistency in a wider range of  $\varepsilon$  and  $\text{tg}\delta$ , a RMT-based sensor with a sensitivity that can be changed and adjusted to diagnose various materials is required. Such a technique for a wide change in the main characteristics of the sensor can be the axial movement of the probe-forming central conductor in the volume of the resonator relative to the aperture plane Fig. 1 a, b [12, 13].



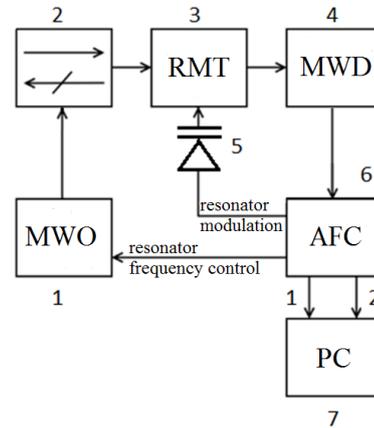
**Fig. 1** – Schematic representation of RMT a) conical type and b) cylindrical type with a movable probe-forming central conductor

This design feature allows you to explore objects regardless of shape and consistency. By changing the position of the probe tip relative to the aperture, it is possible to measure various solid samples such as plastics, ceramics, resins, LCP, various nanostructures, glass, as well as powders and objects of liquid consistency. In particular, promising studies of the latter include: determination of the amount of water in fine powders, blood samples, tissues of living organisms, gasoline, cement, food products, because the sensor based on the RMT with a retractable probe-forming central conductor used in the work allows measuring  $\varepsilon$  in the range of 1-60, and  $\text{tg}\delta$  from 0,0001 to 2.

In the work for the study, two types of the so-called RP construct were chosen conical and cylindrical, were

previously well studied by us in a number of works [8, 12-13]. Numerical studies are carried out by solving the system of Maxwell equations. The problems of modeling electrodynamic processes of interaction between a microwave source and a sample were solved using a software package based on the finite element method [14].

The functional diagram of the microwave local sensor is shown in Fig. 2.



**Fig. 2** – Functional diagram of the microwave sensor: 1 – microwave generator; 2 – ferrite valve; 3 – resonator measuring transducer; 4 – detector; 5 – varicap; 6 – AFC; 7 – personal computer

The main feature of such a scheme for generating a package of fundamental signals is to reduce the effect of modulation in the automatic frequency control (AFC) system on the noise level in both channels for extracting signals  $\delta f/f$  and  $\delta Q/Q$  through modulation of the resonant frequency of the probe using a varicap (5) [15]. The  $\delta Q/Q$  and  $\delta f/f$  signals are determined by the voltage level at the modulation frequency (for the  $\delta f/f$  signal) and at the doubled modulation frequency (for the  $\delta Q/Q$  signal) taken from outputs 1 and 2 of the AFC, respectively.

## 3. DESCRIPTION AND ANALYSIS OF THE RESULTS

Characteristics of conversion of fundamental signals of the sensor based on the cone-type RP when changing the position of the tip relative to the aperture are shown in Fig. 3.

In Fig. 3, the region with negative values of  $H_p$  along the abscissa axis corresponds to the immersion of the tip into the aperture. The area with positive  $H_p$  values corresponds to the protrusion of the tip into the object. It can be seen from the above dependences that when diagnosing objects with high values of dielectric permittivity and loss tangent, it becomes necessary to reduce the inclusion factor of the object by introducing the tip of the probe into the aperture to ensure the resonant mode of operation of the RMT. For an object with low values of  $\varepsilon$  and  $\text{tg}\delta$ , it is necessary to increase the degree of its influence on the resonant properties of the primary converter by immersing the probe-forming central conductor into the material, thereby providing the necessary sensitivity of the sensor. Also, when carrying out diagnostics, it is necessary to control the value of the quality factor, because when the tip is

extended into the object, its value can significantly decrease, and when immersed inside, the RP at a certain stage will no longer change.

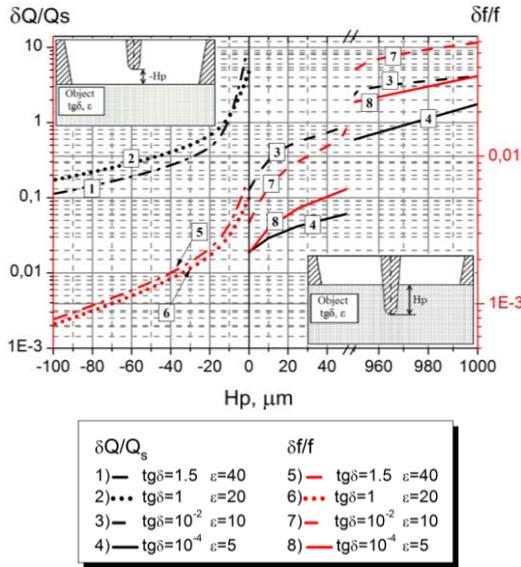


Fig. 3 – Characteristics of the transformation of a cylindrical RMT with a movable probe-forming central conductor

A resonator pickup with a coaxial aperture and a movable center conductor will differ from a classic quarter-wave pickup by a strong loss effect. When immersed inside the tip, it will be a coaxial resonator with a shortening capacitance. When extended, the tip will be a resonator, the open end of which is loaded on a monopole antenna.

In general, these results convincingly testify to the wide possibilities to control the influence of the object on the quality factor of a resonator sensor with a coaxial aperture. In fact, these dependences quantitatively illustrate the influence of the coefficient of inclusion of an object in the electromagnetic field of the resonator, which can be used to select the optimal value of the operating frequency of the sensor and its sensitivity. We also note that this technique is an effective alternative to a similar change in the sensor sensitivity using the gap between the object and the aperture plane [9, 13, 16].

The use of such a sensor in practice may be inefficient due to the dependence of fundamental signals on the position of the tip relative to the end of the aperture. When restoring the profiles of electrophysical parameters of objects, the value of  $H_p$  will affect the resulting signal, thus being an interfering factor. The solution to this problem can be the use of a hybrid signal  $N$ , based on the ratio of fundamental  $(\delta Q/Q)/(\delta f/f)$ , similar to the variant with the classical quarter-wave RMT [8]. The behavior of such a signal with a change in the position of the tip is very clearly shown in Fig. 4.

In particular, the above figure convinces that the invariance of the combined signal to the amount of displacement (or position) of the tip relative to the aperture is not always observed. It is shown that in the resonator volume region, when the tip is in the aperture, the value of the combined signal does not depend on the extension value, except for points close to zero. In the case when the tip extends into the object, a similar

picture is observed. By excluding the contact measurement mode, it can be seen that a significant disturbance in this range will not occur.

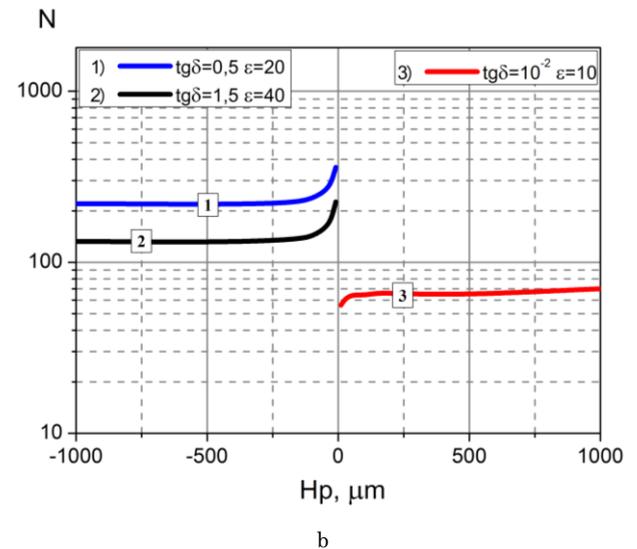
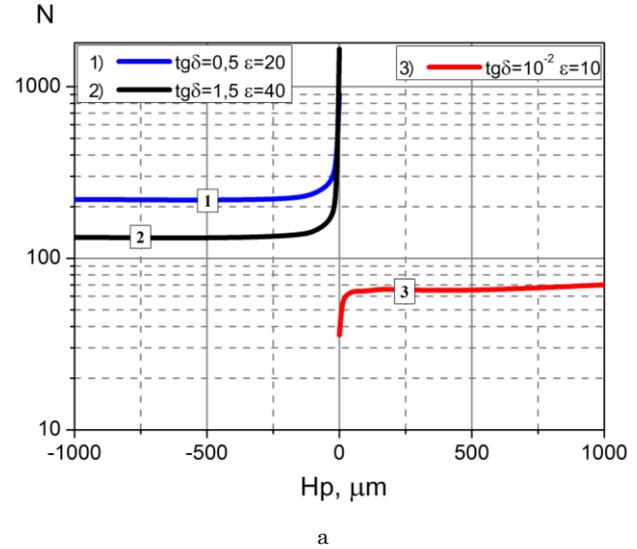


Fig. 4 – Characteristics of the conversion of the combined signal to the amount of movement (or position) of the tip relative to the aperture a) including the contact mode, b) without the include of the contact mode

The given dependences convince us that the contact and near-contact mode of operation of the sensor must be studied in more detail, having determined the criteria for violating the fulfillment of invariance during measurements.

Fig. 5 shows the dependences of the parameters of the RP of an unloaded object on the range of movement of the tip along the vertical.

It can be seen from the dependences presented that the fundamental signals  $Q_0$  and  $f_0$  depend on the amount of displacement of the central conductor relative to the RMT aperture. It should also be noted that the shift of the resonant frequency occurs linearly, and the change in the quality factor is non-linear. There can be several factors that cause this phenomenon: losses due to radiation from the aperture, which increase

significantly with the appearance of a field of a wave nature when the tip leaves the RMT volume, and changes in propagation conditions due to a change in the design, or rather, the length of the movable central conductor of the coaxial. In order to minimize radiation losses, it is necessary to short-circuit the open end of the resonator. The determination of the optimal matching

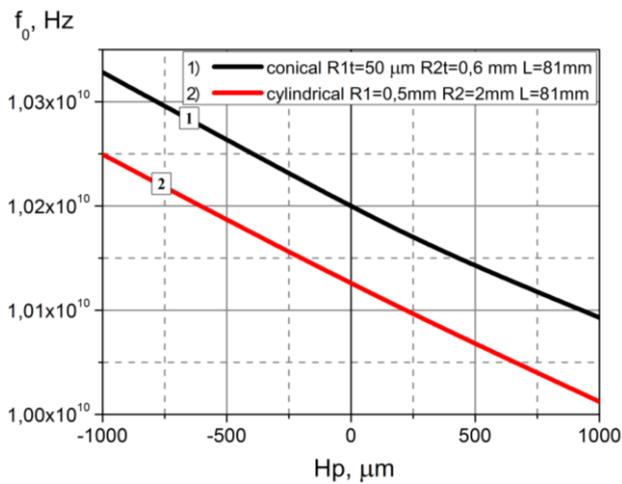
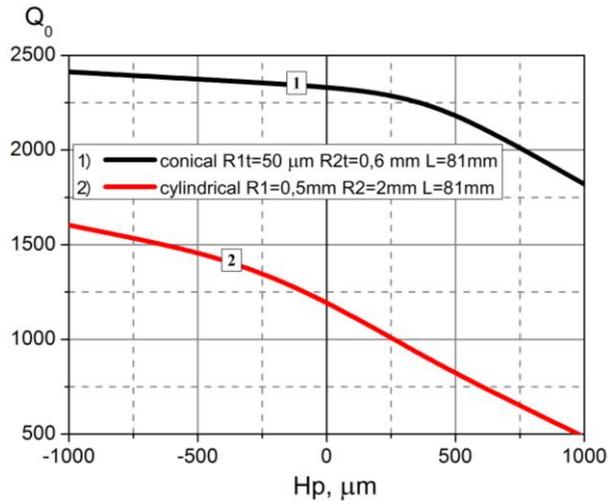


Fig. 5 – Characteristics of the transformation of the conical and cylindrical RP, unloaded by the object

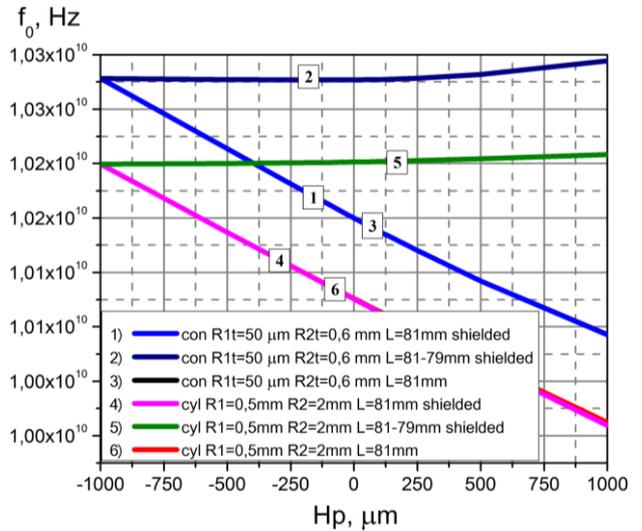
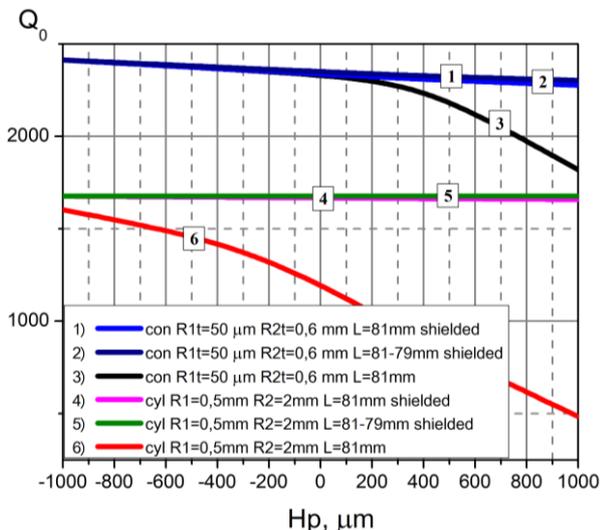


Fig. 6 – Characteristics of the conversion of conical and cylindrical RP, unloaded by the object, taking into account radiation losses and adjusting the length of the RP

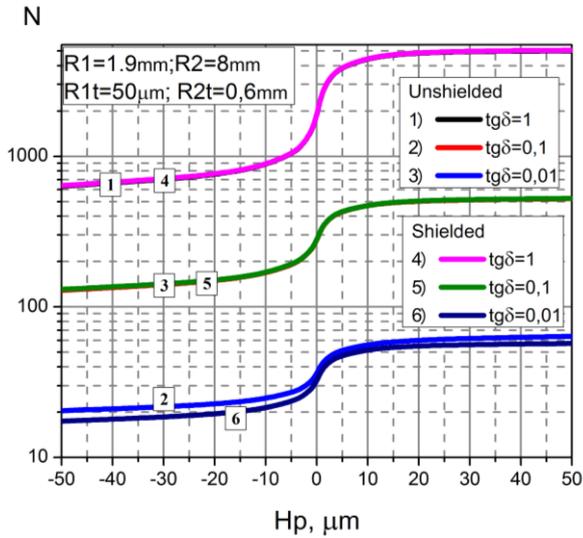
conditions will be carried out by changing the length of the resonator  $L$  depending on the change in the value of  $Hp$ . Fig. 6 shows the results of studying the fundamental signals of the RS at the moment of changing the position of the tip in the coaxial with the closed and open end of the resonator, as well as with a smooth change in the length of the resonator.

The above dependences clearly show that the value of the initial quality factor of an empty resonator is affected only by radiation losses, and for the conical design of the RP, this manifests itself only at  $Hp \gg 0$ , while for the cylindrical one in the entire range under study. By shorting the open end of the resonator, one can obtain a signal  $Q_0$ , which will not depend on the amount of extension of the tip.

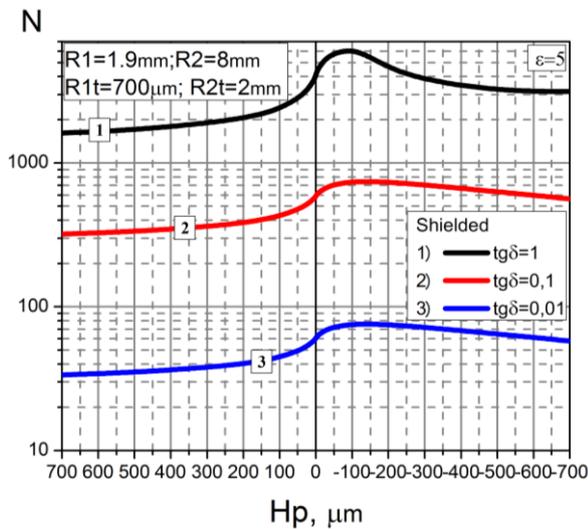
Radiation losses have such a small effect on the signal  $f_0$  that they can be neglected in further studies. From the graph in Fig. 6b, it can be seen that the resonant frequency of the resonator unloaded by the object depends only on matching the lengths of the central and outer conductors of the coaxial. When changing the value of  $L$  in the range from 81 to 79 mm, depending on the extension of the tip, keeping the lengths of the outer and central conductors equal, it can be seen that the signal  $f_0$  does not depend on the extension value. However, it should be noted that in practice such an approach is impossible due to the design features of the RP, and the signal changes under the influence of this factor are so small that they can be neglected in further studies. However, such a feature of the signal  $\delta f/f$ , found during the simulation, is very useful in analyzing the convergence of the results obtained. In the absence of an object, as can be seen in Fig. 6, by eliminating radiative losses, it is possible to obtain measurement information signals that will weakly depend on the amount of extension of the center conductor.

The characteristics of the combined signal conversion, taking into account all the factors considered above, in the near-aperture range of changes in the value of  $Hp$  when diagnosing objects with different  $\text{tg} \delta$ , are shown in Figs. 7.

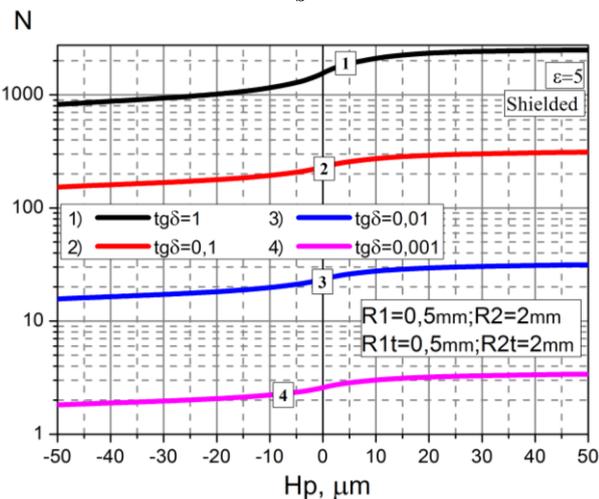
The above dependences draw attention to the fact that when using a cylindrical RP construct, more linear characteristics of the combined signal can be obtained.



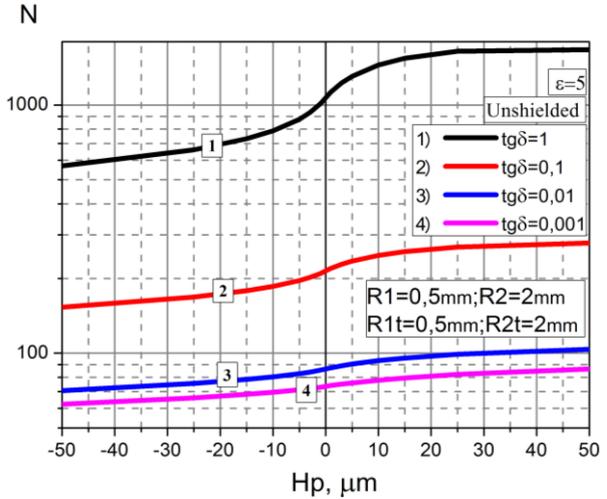
a



b



c



d

Fig. 7 – Invariance of the combined signal to the amount of displacement (or position) of the tip relative to the aperture in the near-aperture region (a, b) of a conical RP and a cylindrical RP (c, d)

Given that the storage part does not affect the characteristics of the field distribution, and the aperture assembly in both constructs is identical, it is logical to assume that the reason for this physical phenomenon is a stronger connection between the storage and aperture regions in such a construct [9]. In a rather narrow range of  $H_p$  values, the differences between an open cone resonator and a closed one are minimal. Apparently, this is due to the fact that the wave component with such a geometry of the aperture part of the RP begins to manifest itself at much higher values of  $H_p$  [3], as shown in Fig. 5. When shielding the volume of the cylindrical RMT construct, a more correct display of the measurement result of objects with a low loss tangent is observed.

The change in the combined signal in the region of transition from vacuum to the object, which is common for both RP constructs, is due to the gradient of electrophysical properties at the probe-object interface. With increasing losses in the object, the change in the signal in this area is also more significant. When using RS with a large tip radius, this effect is more pronounced, which was to be expected for understandable physical reasons.

#### 4. CONCLUSION

The paper considers the principles of implementation of local microwave diagnostics of materials in a wide range of their electrophysical parameters using aperture resonator sensors. To change the degree of inclusion of the object in the electromagnetic field of the aperture coaxial resonator sensor in order to expand the range of values  $\epsilon$  and  $tg\delta$  controlled by it, it is proposed to change the position of the tip of the probe relative to the edge of the waveguide plane. It has been established that this approach is universal, since it allows diagnosing various objects with one applicator.

Quantitative data are presented, which also convince of the uniqueness of the developed method. It has been

established that the use of the developed RP in practice can be complicated by the influence of such interfering factors as: radiation losses from the resonator aperture, mismatch of propagation conditions, avoidance of the so-called. quarter-wavelength, violation of the condition of smallness of perturbations at high values of the permittivity and loss tangent of the object under study. Approaches to reduce the influence of these factors are proposed.

It has been established that the use of a hybrid signal of the form  $(\delta Q/Q)/(\delta f/f)$  makes it possible to remove part of the influence of the interfering factors considered in the work. However, as practice has shown, its use will be effective only in one of its modes of operation, either when immersed in the aperture, if the object has high losses, or when moving towards the surface of the object with low losses. It is shown that the use of a cylindrical RP construct has a number of advantages over a conical one.

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## Розширення функціональних можливостей резонаторних апертурних датчиків для НВЧ діагностики малорозмірних об'єктів

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У роботі розглядаються основні принципи функціонування резонаторних датчиків з рухомим зондоутворюючим центральним провідником і підходи, спрямовані на оптимізацію їх вимірювальних характеристик. Показано внесок втрат, пов'язаних із виникненням хвильового поля, неузгодженістю умов поширення в обсязі резонансного вимірювального перетворювача (РВП), а також прийоми, спрямовані на виключення їх впливу.

Представлені кількісні дані, що характеризують роботу сенсору, що перебудовується, в межах кожного з двох розглянутих режимів функціонування, а також переконують у необхідності оптимізації геометрії конструктиву резонаторного зонда (РЗ). Наведено порівняльний аналіз використання як РВП зондів конусного та циліндричного типів. Показано, що екранування зразків має набагато більший сенс для використання циліндричного конструктиву при діагностиці об'єктів з низьким тангенсом кута втрат. Отримана інваріантність гібридного сигналу  $(\delta Q/Q)/(\delta f/f)$  до впливу заважаючих факторів, обумовлених зміною геометрії апертурного вузла сенсора при переміщенні вістря зонда, та ступеня включення об'єкта в електромагнітне поле резонатора.

**Ключові слова:** НВЧ діагностика, Вимірювання діелектричної проникності, Відкритий коаксіальний зонд, Відстань між зондом та зразком, Електромагнітне моделювання.