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REGULAR ARTICLE

Methods for Controlling the Locality of Coaxial Resonator Probes in Microwave Sensorics

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This paper discusses methods for controlling the locality of microwave diagnostics of small objects using resonator aperture sensors with coaxial symmetry. The paper presents the results of a study of the electrodynamic properties of coaxial resonator probes developed for local microwave diagnostics of physical objects. An analysis of the factors that in-fluence the depth of penetration of the electromagnetic field into the object under study was carried out. Attention is paid to analyzing the influence of the aperture assembly geometry on the sensor's measurement signals and the electrodynamics of processes within the model, which was developed using a numerical method. The influence of the gap in the probe-object system, as well as the tip size and shape, on the field distribution of a classic quarter-wave resonator measuring transducer is demonstrated. The results of a study of a compact version of the coaxial probe are presented. The effect of reducing the storage section of the resonator on the field distribution in the object under study is demonstrated. It is shown how significantly the electric field energy and the achievable locality of measurements change when filling the storage section of the resonator with fluoroplastic.

Keywords: Resonator measuring transducer, Microwave sensor, Coefficient of inclusion of an object in the resonator field, Permittivity, Resonant frequency, Quality factor, Conversion characteristics.

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1. INTRODUCTION

Scanning microwave microscopy (SMM) is a powerful, high-resolution technique to characterize material properties at the nanoscale. Modern local microwave sensors are designed for the diagnostics of materials, films, and nanostructures with high spatial resolution. One of the most common elements of such systems is coaxial resonator probes (RP), which excite and record local microwave fields in a limited spatial region [1 - 3]. They are often used to monitor semiconductor parameters, determine free and bound water in biological samples, measure grain moisture content, and diagnose fine powders, resins, etc. [4].

A key characteristic of such probes is the achievable localization of the field near the tip (central core), which determines the spatial resolution and sensitivity of the sensor. Unlike scanning microwave microscopy, which strives to increase the localization of the probe-sensor interaction with the object, local microwave sensing requires obtaining some integrated information about the properties of small objects. Therefore, it is important to be able to select the locality depending on the object's surface geometry and the specific properties being diagnosed. Locality, in turn, is limited by the optimal coefficient of inclusion of the object in the resonator's electromagnetic field. A high value of this coefficient can lead to a critical drop in the Q-factor, while a low value can lead to poor sensitivity of the sensor. Therefore, locality control also involves optimizing the field distribution while maintaining a high Q-factor and resonance stability, since it is information about the nature of the field distribution in the area of the strongest probe-object interaction that determines the achievable locality of the sensor.

This paper addresses the general problem of identifying and validating methods for varying the locality of near-field resonator probes with coaxial symmetry depending on the electrophysical properties of the objects.

2. DESCRIPTION OF THE OBJECT AND RESEARCH METHODS.

The probe is the key physical and technical element of local microwave diagnostics and SMM. The authors of [5] even call it the heart of the setup, which further emphasizes the importance of studying its electrodynamic properties. Analysis of previous developments shows that resonator measuring transducers (RMTs)

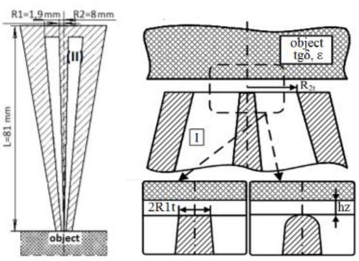

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Fig. 1 – a) Schematic representation of a classic quarter-wavelength RP; b) schematic representation of the probe aperture unit

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with a coaxial measuring aperture [1-5], schematically shown in Fig. 1 [6], are of greatest practical interest.

Based on the results of numerous studies, it can be concluded that the geometry of the aperture-forming region (I) in such a design is virtually independent of the electrodynamics of the accumulation region (II). Therefore, it can be concluded that it is the geometry of the aperture unit of the resonator probe that almost uniquely determines the spatial distribution of the probing microwave field in the object. As shown in several studies, the near field penetrates the object to a depth comparable to the radius of the probe tip [7, 8]. The electrodynamic properties and structure of the object affect the probing depth practically only within the limits of the evanescent field distribution. This is demonstrated by the dependencies presented in Fig. 2.

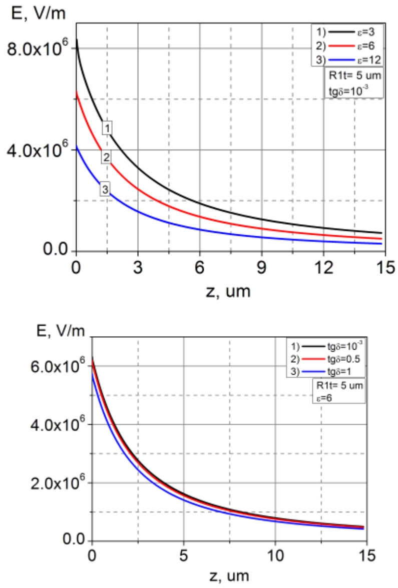


Fig. 2 – Field distribution by depth depending on the electrodynamic parameters of the object

Fig. 2 shows examples of field distributions obtained by numerically solving Maxwell's equations using the finite element method for aperture geometry $R_{1t} = 5$ μm and $R_{2t} = 600$ μm with a spherical tip and various parameters of the studied object. The results of a more detailed study are presented, e.g., in [6].

The theoretical studies in this work were performed numerically for the electrodynamic structure of a coaxially symmetric resonator probe, shown in Fig. 1 with different aperture assembly variations. The operating frequency of the quarter-wavelength RP was selected to be in the region of 10 GHz. The intrinsic quality factor of the RP unloaded by an object is approximately 2300.

The studies were carried out by finding the electromagnetic field distribution, the resonant frequency, and the quality factor of RP from the solution of Maxwell's equations using the finite element method [9].

3. DESCRIPTION AND ANALYSIS OF THE RESULTS

Coaxial probes are so-called transmission line sections closed under resonant conditions (usually quarter-wavelength resonators). The field localization at the probe tip is determined by the aperture geometry, the electric field distribution between the central and outer conductors, and the properties of the dielectric in the interaction zone with the object. In the near field, a quasi-static distribution is formed, similar to the field of a microcapacitor interacting with a localized area of the surface of the object being studied.

The influence of the tip radius and shape is demonstrated by the conversion characteristics shown in Fig. 3.

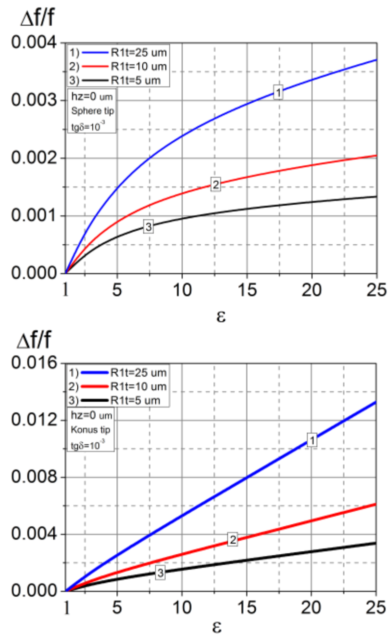


Fig. 3 – Characteristics of the transformation of the RP for different shapes and radii of the tip

As expected, decreasing the tip radius results in weaker signals. It's also worth noting that when using a truncated cone-shaped tip, the fundamental signal dependence is virtually linear. A more detailed study of this phenomenon requires analyzing the electrodynamic properties of such a probe. The field distribution for both tip shapes is shown in Fig. 4.

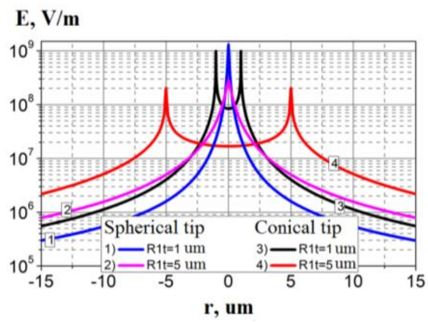


Fig. 4 – Field distribution over the surface for different R1t for spherical and conical tip shapes

As can be seen, using different tip shapes of the same size yields different results. A spherical tip is characterized by a quasi-Gaussian distribution. A conical tip exhibits what's known as a tubular field. Thus, we can conclude that a spherical tip exhibits greater locality, as it has a single extremum located under its center. A conical tip typically has two extrema, which results in the field strength maximum being located at the periphery.

Since localized microwave diagnostics is a non-destructive diagnostic method, measurements are often performed in non-contact mode. The gap between the probe and the object also contributes to the locality of the measurements. The influence of the gap on the conversion characteristics is shown in Fig. 5.

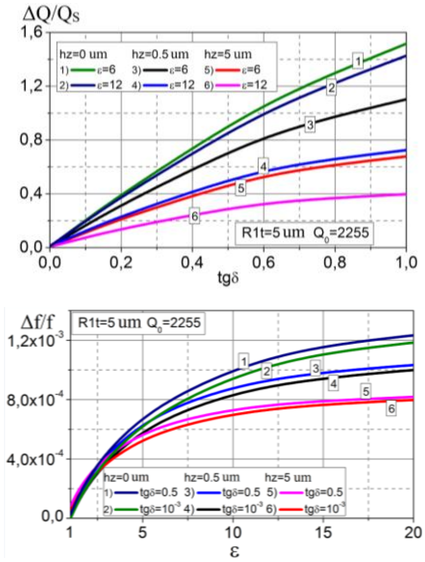
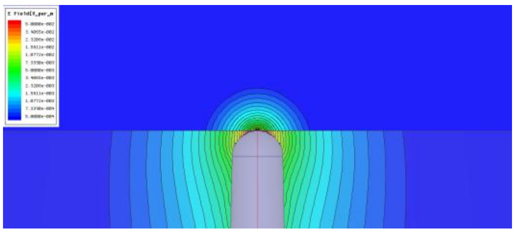


Fig. 5 – Dependence of fundamental signals on the electro-physical parameters of an object for different gap sizes

The gap significantly reduces the magnitude of the fundamental signals. As expected, the coefficient of inclusion of the object in the resonator field also decreases. However, the influence of this factor on locality can only be assessed with diagrams of distribution of field in the object, which can be obtained using the data in Fig. 6 [4].

As can be seen from these data, the gap significantly reduces not only the degree of inclusion of the object, but also the locality of the measurements.



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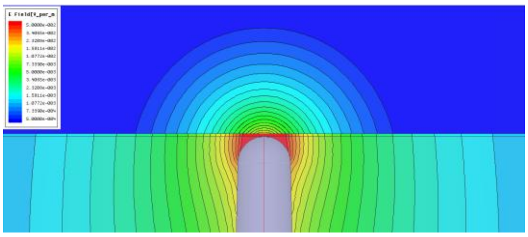

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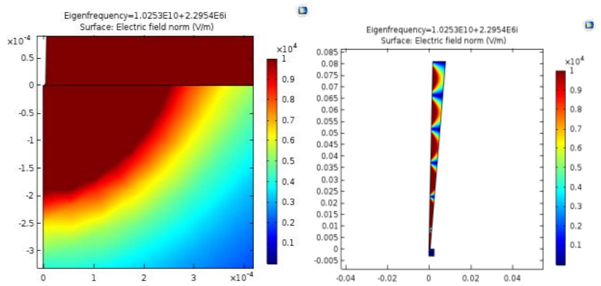
Fig. 6 – Distribution diagrams of the total field in an object in the absence (a) and presence of a gap (b) for a spherical tip

One more geometric method for controlling locality can be changing the length of the coaxial cable. Fig. 7 shows the electric field diagrams of such a probe compared to a standard one.

Evidently, shortening the probe by almost a factor of 4 significantly improves the locality of measurements. It is also worth noting that the aperture assembly remains unchanged. This effect is comparable to replacing the tip with one that is almost 10 times smaller.

Filling the coaxial with a substance with low permittivity will obviously also affect the probe's electrodynamic parameters and the locality of measurements.



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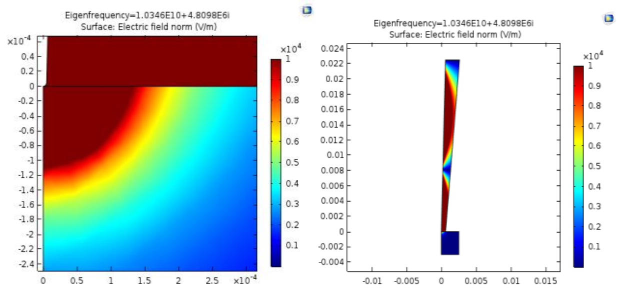

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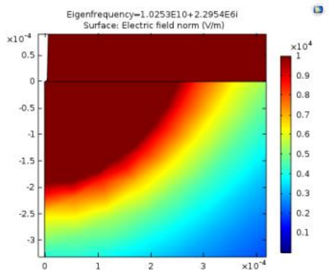
Fig. 7 – Distribution diagrams of the total field in the object in a standard probe (a) and in a shortened one (b)



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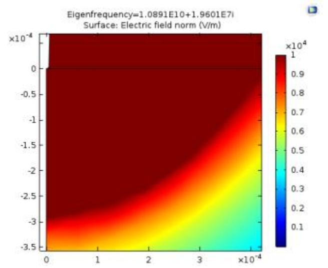

b

Fig. 8 – Distribution diagrams of the total field in the object when the probe is filled with air (a) and fluoroplastic (b)

Fig. 8 shows the field diagrams obtained by simulating a standard probe filled with fluoroplastic with $\varepsilon = 2.1$. For comparison, the same figure also shows the results for the classical case.

In particular, filling the coaxial tube reduces locality. This can be explained by a significant decrease in the resonator's Q factor.

Thus, the highest locality is achievable using a small probe with a spherical tip, submicron size, and no internal filling.

4. CONCLUSION

Managing the locality of coaxial resonator probes is a key challenge in modern local microwave sensing. This paper examines the main methods for addressing this challenge. Results from the study of probe aperture assembly geometry, its length, and the effect of the coaxial dielectric filling are presented. In practice, these methods should be complemented by optimal selection of coupling types, matching methods, and algorithmic data processing to improve the efficiency of local reconstruction. The combined use of these approaches ensures the achievement of micron and submicron spatial resolution necessary for the analysis of modern nanomaterials and microelectronic structures.

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Методи управління локальністю резонаторних зондів коаксіального типу у НВЧ сенсориці

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У роботі обговорюються способи здійснення управління локальністю НВЧ діагностики малорозмірних об'єктів при використанні апертурних резонаторних сенсорів з коаксіальною симетрією. Наведено результати дослідження електродинамічних властивостей коаксіальних резонаторних зондів, розроблених для локальної НВЧ діагностики фізичних об'єктів. Проведено аналіз факторів, що впливають на глибину проникнення електромагнітного поля углиб досліджуваного об'єкта. Особливу увагу приділено аналізу впливу геометрії апертурного вузла як на вимірювальні сигнали сенсора, так і на електродинаміку процесів в межах моделі, яка була розроблена з використанням чисельного методу. Показано вплив зазору в системі зонд-об'єкт, розміру та форми вістря на розподіл поля класичного чвертьхвильового вимірювального резонаторного перетворювача. Наведено результати дослідження малогабаритної версії коаксіального зонда. Продемонстровано вплив зменшення накопичувальної частини резонатора на розподіл поля у досліджуваному об'єкті. Показано, наскільки сильно змінюється енергія електричного поля та досяжна локальність вимірювань при заповненні накопичувальної частини резонатора фторопластом.

Ключові слова: Вимірювальний резонаторний перетворювач, НВЧ сенсор, Коефіцієнт включення об'єкта в поле резонатора, Діелектрична проникність, Резонансна частота, Добротність, Характеристики перетворення.