NEAR-FIELD MICROWAVE MICROSCOPE WITH AN ANNULAR GENERATOR

V.V. DANILOV, V.S. SIDORENKO, YU.O. GAIDAI, O.V. SIN'KEVICH

Taras Shevchenko Kyiv National University, Faculty of Radiophysics
(2, Academician Glushkov Ave., Build. 5, Kyiv 03127, Ukraine)

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A new method of investigating insulator parameters in the framework of near-field microwave microscopy, which provides a high resolution of detecting small inhomogeneities $\Delta\varepsilon$ of the dielectric permittivity, has been proposed. The essence of the method is an application of a multimode microwave annular generator, where the frequency shift of generation modes depends on the dielectric permittivity of the investigated specimen. A high accuracy of the frequency shift detection and therefore a high resolution of $\Delta\varepsilon$ are ensured by a digital frequency meter.

Introduction

Near-field methods for measuring insulator parameters in microwave and optical wave ranges were developed intensively during last years [1—3]. The results obtained evidence for great capabilities of a new trend, near-field microwave microscopy, which allows visualizing the microtopography of the distribution of inhomogeneities of the dielectric permittivity ε and the dielectric losses of a specimen in various ultra-high frequency (UHF) ranges on the screen of a PC monitor, which is impossible for any other technique [3].

The issue of the resolution enhancement arises soon or later for every method of measurements. The spatial resolution of near-field microscopy is now of the order of 10 nm [4], and its further enhancement is mainly connected with technological problems of the production of the tip needles with the end radius of several nanometers. On the other hand, for example, the enhancement of the $\Delta\varepsilon$-resolution, which is caused by growing requirements to the homogeneity of UHF materials, is confined by an accuracy of conventional passive UHF routines. Those routines comprise, as a rule, the measurement of a resonance frequency shift for a certain oscillating structure, which is contained, explicitly or implicitly, in any near-field method. However, if the $\Delta\varepsilon$ inhomogeneities are small, the contour of the resonance peak has almost no displacement, so a detection of small shifts of the resonance frequency faces substantial difficulties. Various bridge compensation and modulation methods are used to increase the detection accuracy of such displacements [2, 3].

If the samples to be investigated for inhomogeneity possess dispersion, the measurements should be carried out at various frequencies, which calls for the variation of the microscope operating frequency. In order to avoid the replacement of a resonator with the tip needle at the end, a 1-meter coaxial line was used in [1] as a multimode resonator, whose longitudinal modes resonate in a wide frequency range from 0.1 to 50 GHz.

Description of Method and Experimental Part

In the method proposed, a coaxial line of the length $L = 1$ m is also used as a multimode resonator, but is connected so that it creates an annular generator (an analogue of the ring laser but in the UHF range). The idea of the method is that it is not necessary now to measure the position of the resonance line maximum, because when taking advantage of a non-resonance amplifier, the generation takes place at the relevant frequency automatically, and the application of involved bridge compensation and modulation schemes is therefore unnecessary. This makes the installation scheme to be very simple. The generated frequencies and the amplitudes of oscillations are measured by means of a digital frequency meter and a digital voltmeter,

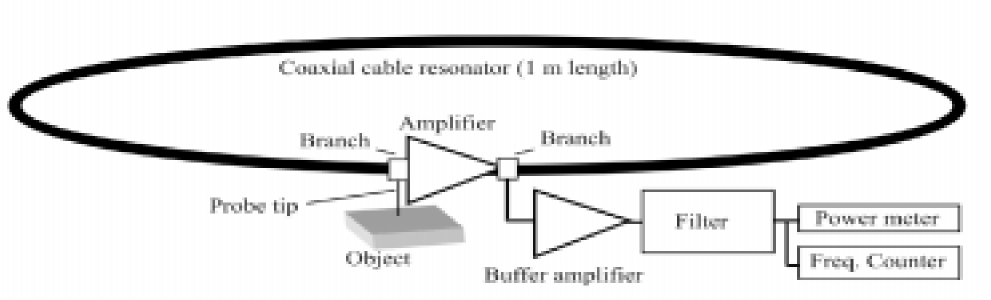

Fig. 1. Block diagram of the experimental set-up.

respectively, which ensures the digital detection of the oscillation frequency shift with accuracy much higher than that of conventional compensation and modulation methods.

The block diagram of such a device for applications in probe near-field microwave microscopy is depicted in Fig. 1. A broadband buffer UHF amplifier is used to decouple components determining the resonance frequency from the variable input impedance of the wavemeter, frequency meter, and voltmeter, as well as their connecting cables. The tees are connection links, being special splitters with tunable components. The dielectric specimen, being brought to the tip, introduces a reactance into the circuit, changing the electrical length of the latter and therefore the frequencies of its resonance modes and the spectrum of generated frequencies.

Two types of oscillations have to occur simultaneously in the scheme of Fig. 1. The first type is analogous to oscillations in a ring laser, where an integer number of waves should be packed along the ring length to satisfy the phase synchronism and thus the resonance conditions for waves that run along the ring. The amplifier becomes an energy pump, which compensates the attenuation in the circuit and ensures the regime of multimode generation with the intermode frequency interval $\Delta f = v_\mathrm{f}/L = 200$ MHz for the 1-meter cable in use.

On the other hand, the impedance matching between the amplifier input/output and the cable of the annular resonator is not perfect, and an extra regime of standing waves emerges in the circuit with resonances at frequencies corresponding to an integer number of halfwaves along the cable length, i.e. the spectrum of the longitudinal resonance modes arises with the frequency interval between modes $\Delta f = v_\mathrm{f}/2L = 100$ MHz for the same cable.

The combination of those two types of oscillations results in an equidistant spectrum of generated frequencies with the intermode interval of 100 MHz, overlapped by another equidistant spectrum with the intermode interval of 200 MHz, so each second generated mode in the ultimate spectrum is larger in amplitude.

Similarly to the case of a ring laser, where the spectrum of generated modes is confined by a bandwidth of the amplifier channel, it is also confined in our case by a bandwidth of the UHF amplifier, so the latter must be broadband.

Experimental data concerning the spectrum structure of the excited oscillations are presented in Fig. 2. It is clear that in full agreement with the said above, the modes of the running wave with the interval of 200 MHz have larger amplitudes than the modes of the standing wave with the interval of 100 MHz, because the coincidence of both resonance conditions, i.e. $\Delta f = v_\mathrm{f}/2L$ and $\Delta f = v_\mathrm{f}/L$, and therefore the summation of amplitudes of the waves of both kinds take place for the former mode.

The spectrum of such a resonator is not necessarily equidistant. If the dielectric permittivity of the sample is inhomogeneous in the generator operating bandwidth, i.e. there is a substantial dispersion, then the boundary conditions for each mode will be different and the frequency interval between modes will change.

It is difficult to detect those small variations in a passive regime of the known compensation and modulation methods. But in the proposed active regime of generation, this becomes possible making use of a high-accuracy digital frequency meter.

For the interpolation estimation of the $\Delta\varepsilon$-resolution capability of the method, a dependence of the frequency shift of the generated modes on dielectric permittivity was experimentally investigated for insulators with known ε like teflon, polycor, and barium titanate (Fig. 3).

For example, measurements carried out on a polycor dielectric plate with $\varepsilon = 9.6$ gave the following results: an approaching of the plate to the tip shifted the

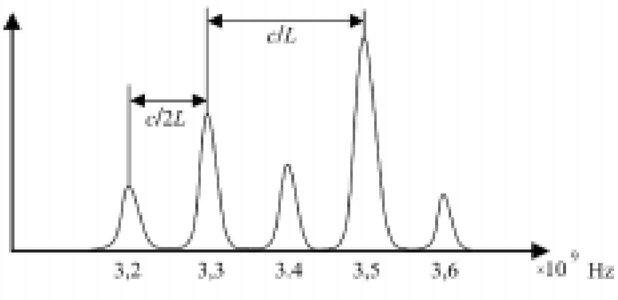

Fig. 2. Modes of the annular UHF generator

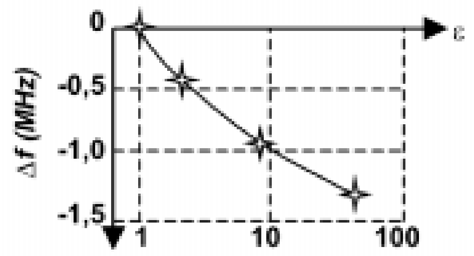

Fig. 3. Dependence of the frequency shift of the generated mode on the dielectric permittivity ε of the studied materials

generated frequency from 3.600553 to 3.599631 GHz, i.e. by 948 kHz. To accelerate the counting routine, we selected the least significant digit of the frequency meter to be of 1 kHz, the relevant detection resolution of $\Delta\varepsilon$ being approximately of 0.9×10^{-6}. The registration system in this regime is able therefore to distinguish millionth parts of the ε-variation. Even polyfoam induces the shift of the generated frequency by 10 kHz, i.e. its ε is of the order of 1.09.

We used a Ch3-34A frequency meter with a Ya3Ch-51 UHF unit, which made it possible, taking advantage of the relevant prolonging of the counting time, to increase the accuracy of the $\Delta\varepsilon$-indication by a factor of 100 in the investigated frequency range, and to measure, in principle, those values of ε which differ from 1 by a factor of 1000 less than that for polyfoam. Thus, in the framework of the suggested method, the recording system has great capabilities as to the $\Delta\varepsilon$-resolution. Providing such a high accuracy, several destabilizing factors put themselves in the forefront, e.g., fluctuation noises of the generator, the dependence of the system parameters on the ambient temperature, humidity, atmospheric pressure, as well as on the presence or absence of the contact with a specimen (there is a non-controlled gap between the tip and the dielectric specimen). At present, the studies are carried out concerning the classification and minimization of errors induced by those destabilizing factors.

Conclusions

An original method has been proposed for near-filed microwave microscopy, which ensures a high resolution when measuring the topography of the distribution of inhomogeneities of the dielectric permittivity, $\Delta\varepsilon$.

The regime of multimode generation allows one to perform a parallel spectral analysis of the dielectric properties of the investigated specimen in a certain frequency range.

For the possibilities of the method to be completely brought into action, it is necessary to carry out additional studies of destabilizing factors with the aim of their classification and minimization of relevant induced errors. It should be noted that those errors are inherent in every near-field measuring system, but they are not at the forefront in the passive methods of measuring with their low resolution of $\Delta\varepsilon$.

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БЛИЖНЬОПОЛЬОВИЙ МІКРОХВИЛЬОВИЙ МІКРОСКОП НА ОСНОВІ КІЛЬЦЕВОГО ГЕНЕРАТОРА

В.В. Данилов, В.С. Сидоренко, Ю.О. Гайдай, О.В. Сінькевич

Резюме

Запропоновано нову методику дослідження параметрів діелектриків для ближньопольової мікроскопії, яка забезпечує високу роздільну здатність реєстрації малих неоднорідностей діелектричної проникності — $\Delta\varepsilon$. В основі методики лежить використання багатомодового мікрохвильового кільцевого генератора, в якому зсув частот мод генерації залежить від діелектричної проникності досліджуваного зразка. Висока точність реєстрації зсуву частоти генерації і, отже, висока роздільна здатність за $\Delta\varepsilon$ забезпечується цифровим частотоміром.