PHYSICAL INSTRUMENTS FOR ECOLOGY, MEDICINE, AND BIOLOGY

A Method for Calibrating a Strip Resonator Used in Measurements of the Complex Permittivity of Moist Soils and Grounds

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Received March 31, 2005; in final form, June 20, 2005

Abstract—A method for calibrating a microstrip microwave resonator used to measure the complex permittivity of moist soils and grounds is proposed. This method is based on the use of mixtures of a disperse solid substance and aqueous solutions of salts with known values of their complex permittivity. The resonator is composed of two segments of strip lines, the capacitive electromagnetic coupling between which occurs through a container with a moist soil sample. Sandy soil samples wetted by a sodium chloride solution were used as reference samples. The values of their complex permittivity were determined using the generalized refraction model and the reference data for the complex permittivity of a salt solution. A system of algebraic equations was set up, the solution to which, together with the formulas of the refraction model, allowed the complex permittivity of the test soil sample to be reconstructed from the measured values of the resonance frequency shifts and Q factor. The rms errors in measuring the real and imaginary parts of the complex permittivity, which varied over the ranges 4.79–11.03 and 0.39–3.15, were 0.21 and 0.03, respectively.

INTRODUCTION

Radiophysical methods of remote sensing using decimetric, centimetric, and millimetric waves have been widely used to obtain on-line information on the state of the Earth's surface [1–3]. In particular, microwave sounding of moist soils involves measurements and subsequent interpretation of the radar and radiometry characteristics of the soil cover, which are governed by the value of the complex permittivity (CP) of moist soils and grounds [2–4].

Databases on the CP of moist soils and grounds are compiled from experimental data obtained with waveguide and resonator techniques [3–5]. Methods for measuring the CP using strip resonators have been proposed recently in [6, 7]. These methods provide a higher sensitivity of measurements and allow the volume of the measuring container for decimetric waves to be reduced. Reconstruction of the CP from results of measurements with strip resonators is based [8] on analysis of their amplitude–frequency characteristics (AFCs), which are obtained using the numerical algorithms developed for each specific resonator type [9, 10]. The error of measuring the CP by this method was estimated by comparing the measured values to the reference data for substances with known CP values [8].

In this paper, we describe a method for calibrating a microstrip resonator, which allows us to dispense with the development of numerical algorithms for analyzing the AFCs and to perform experimental calibration using substances with known CP values. The resonator was developed based on the device in [7]. Samples of sandy soil wetted by sodium chloride solutions with different concentrations were used as standard samples with known CP values. Their CP values were determined using the generalized refraction model [11–15] and the CP data for a salt solution [16].

A system of algebraic equations was set up based on a set of resonance frequency shifts and the Q factor of the resonator, measured at different values of the sample moisture content and different concentrations of the salt solution that wetted the sample. A solution to this system allowed the volumetric moisture and the concentration of the water solution in a moist sandy soil sample to be reconstructed from the measured values of the resonance frequency shift and Q. The CP error due to the inaccuracies in obtaining the system of algebraic equations and its numerical solution was investigated. To perform independent estimation of the strip resonator calibration errors, we measured the CPs of diethylene glycol and its mixtures with sand in various proportions. The measured values were compared both to the reference data [17] for the CP of ethylene glycol and to the CP for its mixtures with sand, calculated in view of the generalized refraction model [14, 15]. Conclusions about the errors of the proposed calibration technique were based on the results of this comparison.

Cross section 1   Cross section 2
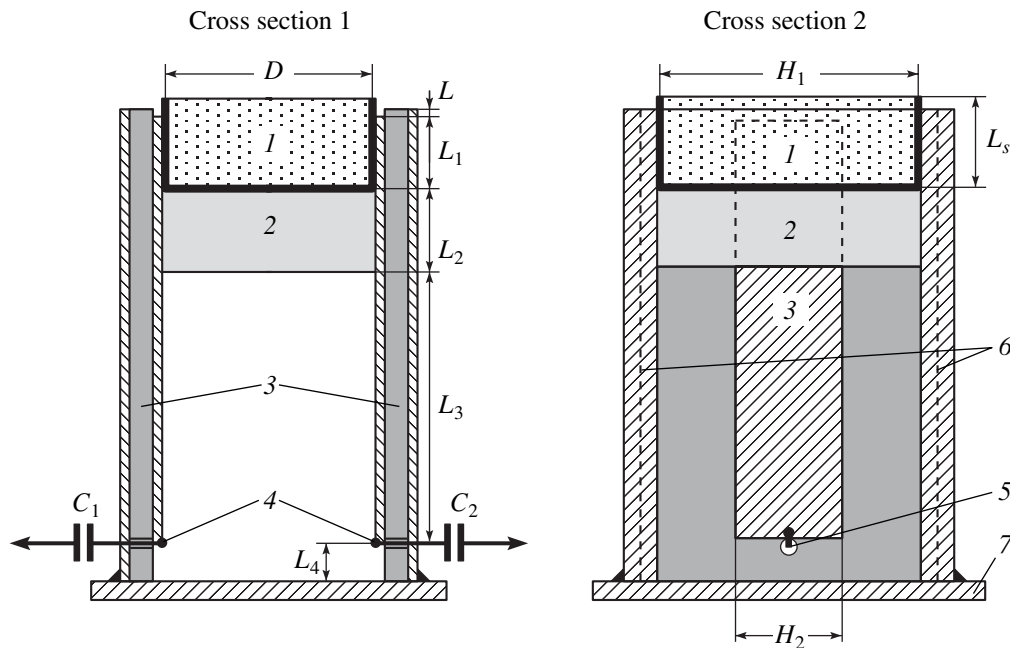
Fig. 1. Diagram of the strip resonator design: (*1*) container with a soil sample, (*2*) Teflon insert, (*3*) strip lines, (*4*) coaxial–strip junctions with capacitive coupling, (*5*) orifices for the capacitive coupling with an input and an output, (*6*) external lateral faces, and (*7*) base of the device.

DESCRIPTION OF THE STRIP RESONATOR UNIT FOR STUDYING COMPLEX PERMITTIVITY. DESIGN CALCULATION AND MEASURING THE AFC OF THE DEVICE

The resonator strip-line transducer under investigation was produced according to [7], with the only difference being that the cross section of its external metal shield is rectangular instead of round. Segments of microstrip lines *3*, which form a resonator, are located opposite to one another (see Fig. 1). The separation between the microstrip lines is fixed by Teflon insert *2*, which is placed at top of the transducer.

The strip lines are made of flan-2.8 material. The microwave power is delivered to (and taken off) the strip lines from the bottom of the device over coaxial–strip junctions *4* and coupling capacitors C_1 and C_2. External lateral faces *6* and base *7* of the device are made from copper plates, to which external conductors of the strip lines are welded. To ensure capacitive coupling, orifices *5* are made in the flan foil. Container *1* with a soil sample is placed in the spatial domain where capacitive coupling exists between the strip line segments and the antinode of the high-frequency electric field is located. A test sample changes the capacitive coupling between the strip line segments; this causes the resonance frequency and the *Q* factor of the resonator to vary, depending on the CP of the test sample.

The Microwave Office software package (Applied Wave Research, www.appwave.com) was used to calculate the dimensions of the resonator components and the values of the coupling capacitors at a given reso-

nance frequency. This package allows the AFC of the resonator to be calculated for varying lengths of the strip line segments, L_1 and L_3; width of the strip conductor, H_2; distance between the strip lines, D; values of coupling capacitors, C_1 and C_2; thickness of the Teflon insert, L_2; complex permittivity ε; sample dimensions D, H_1, and L_s; and spacing L_4 between the input point of capacitive coupling and the resonator base.

The AFC of the resonator was calculated and simultaneously measured using the P4-38 complex transfer constant meter. Figure 2 presets the calculated and measured AFCs corresponding to an empty (air-filled) measuring container. The calculation involved the values of the above parameters that corresponded to the measured dimensions and capacitances of the coupling capacitors, as well as the CPs of the insulating materials used in the resonator. The best agreement between the measured AFC and the calculation was achieved by varying (within 10%) the resonator length L_3 and capacitances of C_1 and C_2. The values of the coupling capacitors at the resonator input and output were selected so that the resonance curves for the electric and magnetic modes of the resonator merged with each other in the region of low-frequency resonances.

It is evident from Fig. 2 that, when the nominal parameters are used, the calculated AFC agree with the measured curve only in the region of one resonance frequency $f = 1790$ MHz. In this case, discordances in the other resonance regions are essential. Our experiments and calculations showed that agreement between the calculated and measured AFCs for frequency $f =$
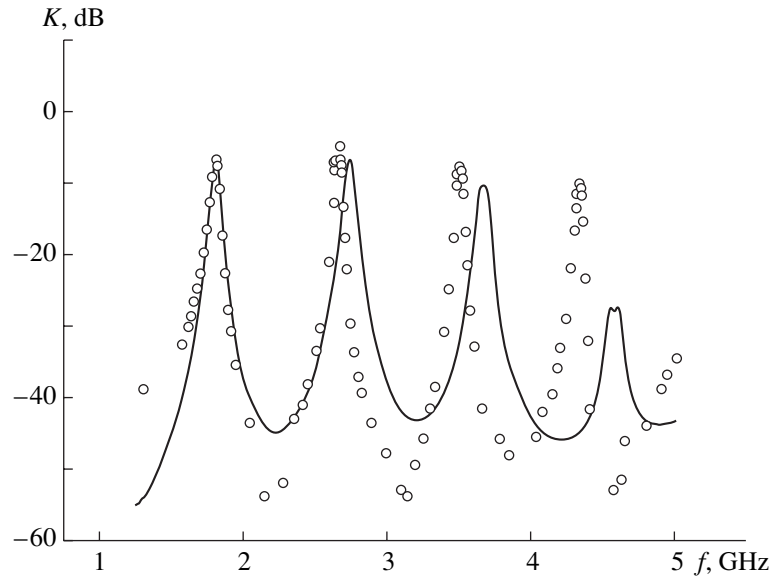
Fig. 2. Measured (dots) and calculated (curve) AFCs of the resonator being tested.

1790 MHz is observed only for sandy soil samples with a moisture content of 5% and under. As a result, the optimization technique is applicable to determination of complex permittivity from the AFC measurements (as was done in [8]) only in this limited range of moisture content. It seems that a more exact algorithm for calculating the AFC of the resonator under investigation, which would allow the technique [8] to be used, may be developed on the basis of quasi-static methods for analyzing strip resonators [10].

An alternative technique has been employed in our study to calibrate the strip resonator under investigation. It is based on the use of calibration samples, for which the CPs for moist soils and grounds are known in advance. In this case, to achieve a good degree of calibration accuracy, it is required that the increments of the sample's CP be sufficiently small. This problem can be solved by involving the refraction model for mixtures of disperse materials and liquids with known CP values [14, 15].

PREPARATION OF CALIBRATION SAMPLES

As was shown in [14], the real ($\varepsilon' = \mathrm{Re}\,\dot\varepsilon$) and imaginary ($\varepsilon'' = \mathrm{Im}\,\dot\varepsilon$) parts of the CP of moist sand wetted by a sodium chloride solution can be calculated using the refraction model:

$$\sqrt{\varepsilon} = \sqrt{\varepsilon_d} + (\sqrt{\varepsilon_{sw}(S)} - 1)W_{sl}, \tag{1}$$

where ε_d is the permittivity of dry sand, $\varepsilon_{sw}(S)$ is the complex permittivity of the sodium chloride solution, $W_{sl} = m_w/((1 - S)\rho_{sl}V)$ is the volumetric content of the solution in the sample, m_w is the mass of water in the

sample, S is the solution concentration, ρ_{sl} is the solution density, and V is the sample volume.

According to the data presented in [13], the accuracies in estimating the real and imaginary parts of the complex refractive index for decimetric waves using formula (1) are 1.2 and 5.2%, respectively, for a volume content of the solution ranging from zero to a total moisture capacity and a solution concentration of 0–5%. The CP for the salt solution was calculated by formula (1) using the following empirical relations for the relaxation Debye parameters [16]:

$$\varepsilon'_{sw} = \varepsilon_{sw\infty} + \frac{\varepsilon_{sw0} - \varepsilon_{sw\infty}}{1 + (\omega\tau_{sw})^2};$$

$$\varepsilon''_{sw} = \frac{\varepsilon_{sw0} - \varepsilon_{sw\infty}}{1 + (\omega\tau_{sw})^2}\omega\tau_{sw} + \frac{\sigma_{sw}}{\omega\varepsilon_0},$$

$$\varepsilon_{sw\infty} = 4.9;$$

$$\varepsilon_{sw0}(T, N) = \varepsilon_{sw}(T, 0)a(N);$$

$$\tau_{sw}(T, N) = \tau_{sw}(T, 0)b(T, N);$$

$$\sigma_{sw}(T, N) = \sigma_{sw}(25, N)c(\Delta, N),$$

$$\tag{2}$$

where N, mol/l, is the normal concentration of the solution;

$$\varepsilon_{sw}(T, 0) = 88.045 - 0.4147T$$
$$+ 6.295 \times 10^{-4}T^2 + 1.075 \times 10^{-5}T^3;$$

$$\tau_{sw}(T, 0) = (1.1109 \times 10^{-10}$$
$$- 3.824 \times 10^{-12}T + 6.938 \times 10^{-14}T^2$$
$$- 5.096 \times 10^{-16}T^3)/2\pi.$$

Quantities $a(N)$, $b(T, N)$, $\sigma(25, N)$, and $c(\Delta, N)$ have the following form:

$$a(N) = 1 - 0.255N + 5.15 \cdot 10^{-2}N^2 - 6.89 \cdot 10^{-3}N^3;$$

$$b(T, N) = 1 + 1.146 \times 10^{-2}TN - 4.89 \times 10^{-2}N$$
$$- 2.97 \times 10^{-2}N^2 + 5.64 \times 10^{-3}N^3;$$

$$\sigma_{sw}(25, N) = N(10.39 - 2.378N + 0.683N^2$$
$$- 0.135N^3 + 1.01 \times 10^{-2}N^4);$$

$$c(\Delta, N) = 1 - 1.96 \times 10^{-2}\Delta + 8.08 \times 10^{-5}\Delta^2$$
$$- N\Delta[3.02 \times 10^{-5} + 3.92 \times 10^{-5}\Delta$$
$$+ N(1.72 \times 10^{-5} - 6.58 \times 10^{-6}\Delta)],$$

where $\Delta = 25 - T[°C]$.

Estimates according to Eqs. (1) and (2) show that, by using dry sand and a sodium chloride solution, one can prepare calibration samples for a range of CP values in which the real and imaginary parts of the CP vary within the following limits: $\varepsilon' = \text{Re}(\varepsilon)$, from 3 to 18; $\varepsilon'' = \text{Im}(\varepsilon)$, from 0 to 15. Calibration samples were prepared by adding a proportioned amount of salt solution with a predetermined concentration to sand samples rinsed with distilled water. Prior to doing this, natural ferromagnetic impurities were removed from the sand. For this purpose, a 2-mm-thick layer of the sand was scattered over a flat surface and impurities were collected upon the magnet poles. The sample was held for 24 h in a hermetically sealed container to allow the moisture to be uniformly distributed over its volume.

Prior to being placed in the resonator, the moist sand was enclosed in a polyethylene container, which, when empty, did not affect the AFC of the resonator after being inserted into it. At the end of the measurements, the sample was weighed, dried for 24 h at a temperature of 105°C, and weighed again to establish the mass of the moisture contained in it. When determining the volume content of the salt solution in the sample, we used reference data on its density [17]. The container volume was found by weighing the distilled water (with known density) that filled it. The CP values for a dry sand ($\varepsilon_d' = 2.727$ and $\varepsilon_d'' = 0.07$) were measured using the waveguide measuring facility [3]. The CP values of the calibration samples were calculated by formulas (1) and (2).

CALIBRATION TECHNIQUE

The calibration was performed for the first resonance frequency $f = 1790$ MHz (see Fig. 2) at temperature $T = 22 \pm 2°C$. Using the P4-38 complex transfer constant meter, we measured the values of resonance frequency shift, $df = f_0 - f_r$ (f_0 is the resonance frequency with the container being empty, and f_r is the res-
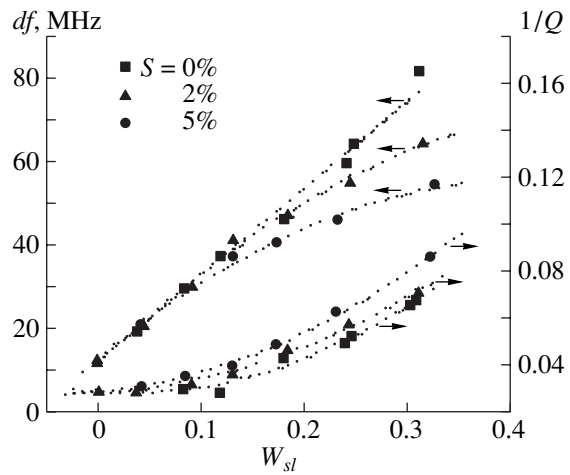

Fig. 3. Resonance frequency shift and reciprocal Q factor as functions of the volumetric content W_{sl} and concentration S of the solution in the sample.

onance frequency when a moist soil sample is placed in the container), and Q factor, $Q = f_r/(f_v - f_n)$, where f_v and f_n are the upper and lower frequency limits at a level of -3 dB. The measured frequency shifts and the reciprocal Q factors as functions of the volume content and concentration of the solution are presented in Fig. 3. The parabolic regression lines were found for these data:

$$df(W_{sl}, S) = a(S) + b(S)W_{sl} + c(S)W_{sl}^2,$$
$$1/Q(W_{sl}, S) = A(S) + B(S)W_{sl} + C(S)W_{sl}^2. \quad (3)$$

Using the data of this table, the parabolic regression lines were found in turn for the coefficients of regression dependences (3) as functions of the solution concentration:

$$a(S) = 12;$$
$$b(S) = 212.43336 + 18.41601S - 3.97399S^2;$$
$$c(S) = -149.04797S + 20.01448S^2;$$
$$A(S) = 0.02872; \quad (4)$$
$$B(S) = -0.02767 + 0.03409S - 0.00406S^2;$$
$$C(S) = -0.48307 + 0.09573S - 0.01631S^2.$$

Substitution of expressions (4) in Eq. (3) yields a system of algebraic equations. A solution to this system allows the volume content W_{sl} and concentration S of the solution present in the sample to be reconstructed from the measured values of the resonance frequency shift and Q factor of the resonator. A numerical solution to this system of equations was sought with the aid of the Mathcad software package. The values of W_{sl} and S thereby obtained make it possible, using Eqs. (1) and (2), to reconstruct the real (ε') and imaginary (ε'') parts of the CP of the calibration samples (Fig. 4).

The values of the coefficients involved in regression equation (3) are presented in the table for different concentrations of the salt solution

Coeffi-cients	Values of the coefficients at solution concentration		
	$S = 0\%$	$S = 2\%$	$S = 5\%$
$a(S)$	12	12	12
$b(S)$	212.43336	233.36941	205.16358
$c(S)$	0	–218.038	–244.87773
$A(S)$	0.02872	0.02872	0.02872
$B(S)$	–0.02767	0.02426	0.04123
$C(S)$	0.48307	0.35685	0.41219

Figure 4 also shows the values of the real and imaginary CP parts, calculated according to formulas (1) and (2) upon substituting into them the W_{sl} and S values obtained by direct measurements of masses and volumes. Comparison of the data from Fig. 4 helps estimate the error due to inaccuracies in constructing empirical regression lines (3) and (4) and numerically solving the system of equations obtained by the substitution of (3) in (4).

The rms deviations, calculated for the entire data set presented in Fig. 4, were as follows: $\sigma(\varepsilon') = 0.17$ and $\sigma(\varepsilon'') = 0.52$. From these estimates, it follows that the errors in reconstructing the CP from results of measurements with a coupled strip resonator are comparable to the errors characteristic of the waveguide bridge measuring circuits [3]. At the same time, these errors do not include inaccuracies in specifying the CPs of the calibration samples, which can be attributed to the approx-
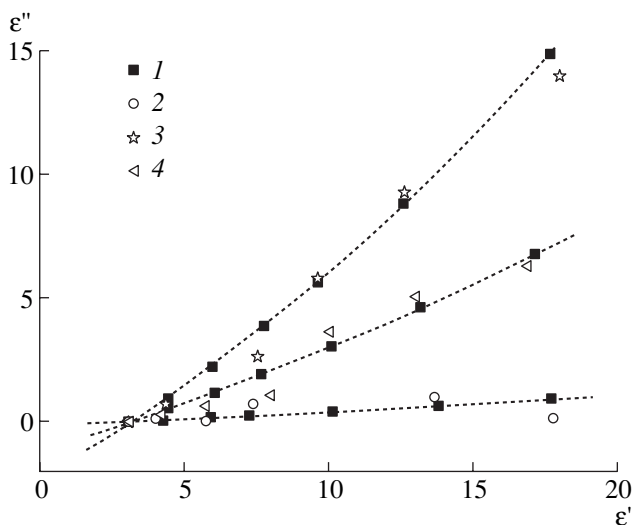
imations accepted in the formulas (1) and (2) of the refraction model and the errors in measuring the parameters involved in them (the permittivity of dry sand, the mass of the water contained in the sample, the solution concentration and density, the sample volume, and the errors of model (2) for the CP of the salt solution). In this connection, we performed an independent estimation of the measurement error using a strip resonator calibrated according to the above technique. As a reference substance, we used diethylene glycol, the CP of which is presented in reference book [18].

DIRECT CHECK OF THE ERRORS OF CP MEASUREMENTS USING A CALIBRATED RESONATOR

Along with pure diethylene glycol samples, samples composed of mixtures of sandy soil and diethylene glycol with different volumetric contents were used to check the calibration error over a wide range of CP values. In this case, the CPs of the reference samples were calculated with the aid of refraction models (1) and (2). All of the measurements were made at temperature $T = 25 \pm 1°C$. During measurements, the frequency shift and the Q factor were determined; then, the S and W_{sl} values corresponding to the equivalent values of the volume content and concentration of the salt solution in water were calculated using Eqs. (3) and (4). Upon substituting these values in Eqs. (1) and (2) in the next phase of calculations, the real and imaginary parts of the complex permittivity were determined for a mixture of sand and diethylene glycol.

For comparison, below, we present the values of the real and imaginary parts of the CPs of the reference samples. The values ε_1' and ε_1'' were calculated using formula (1) and reference data [18], while the values ε_2' and ε_2'' were measured with a calibrated microstrip resonator.

ε_1'	ε_2'	ε_1''	ε_2''
4.789	4.686	0.385	0.435
6.574	6.855	0.839	0.837
6.815	7.188	0.904	0.958
11.03	11.207	3.149	3.221

The rms deviations between the experimental and reference data from this data array are $\sigma(\varepsilon') = 0.21$ and $\sigma(\varepsilon'') = 0.03$. These values are fully consistent with the accuracy of CP measurements with the help of the waveguide bridge circuits [3], which are conventionally used to measure the CP of moist soils and grounds.

Fig. 4. Comparison of the initial and reconstructed CPs (ε', ε'') of different calibration samples: (*1*) initial data and (*2–4*) results of the reconstruction.

CONCLUSIONS

As a result of our study, a technique has been developed for calibrating the CP-measuring facility based on

a strip resonator and designed for measuring CPs in the range of values corresponding to moist and saline soils and grounds. A fundamental feature of the proposed technique consists in the use of calibration samples composed of a mixture of disperse material and liquid with a known CP value. Such an approach makes it possible to produce a sequence of calibration samples with small increments of their CPs that are achieved by dosed adding of liquid. As a result, a set of experimental data can be obtained from the resonance frequency shift and the Q factor that offers a means for constructing a reciprocal interpolation algorithm capable of providing the degree of accuracy acceptable for practical applications.

A direct check of the errors in measuring the CPs of the reference samples using the resonator calibrated in this manner showed that these errors lay within the limits of measurement errors characteristic of the traditional waveguide bridge circuits [3, 4]. Moreover, the use of a strip resonator allows the procedure of sample setting to be substantially simplified, since the measuring container with a sample does not act as a section of a closed waveguide line; it can be freely inserted in the measuring device and removed from it without dismounting the latter. In addition, the sample volume can be reduced significantly in comparison to the waveguide methods of measurements.

ACKNOWLEDGMENTS

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