Electromagnetic properties of water on GHz frequencies for medicine tasks and metamaterial applications

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Abstract. In problems of modern radio physics and medicine it is important to know dielectric permittivity of liquids. Dispersion characteristics of water in UHF frequency band can be used to analyze the states of biological objects, and also to construct materials (metamanerials). The present work is intended to study the material properties of water in UHF frequency band based on two different techniques: Nicolson-Ross-Weir (NRW) [1] and the Active Nearfield Diagnostics [2].

1. Introduction
In problems of modern radio physics and medicine the knowledge of electromagnetic properties of liquids are very relevant. The dispersion characteristics of liquids in UHF frequency band are important to study properties of metamaterials containing water as a material of unit cells. In medical applications the non-invasive methods of biological object analysis become very relevant [3].

2. Nicolson-Ross-Weir Method
The Nicolson-Ross-Weir method [4] of measuring the material properties of substances under study is related to UHF methods. The main idea of the method is to measure the impedance on the dielectric-air boundary as shown in Fig.1, 2. This method allows not only to obtain the value of the impedance by means of S-parameter measurements, but also the phase value. These parameters allow to extract the material properties of the studied substance. One can extract the material properties (the real and imaginary parts of the dielectric permittivity) by means of the NRW method [4]. Here we consider it in details.

It is well-known that the dielectric permittivity and magnetic permeability of a substance can be represented in the following form [1]:

\[ \varepsilon = (\varepsilon' - j\varepsilon'')\varepsilon_0 \quad \mu = (\mu' - j\mu'')\mu_0 \]

(1)

where \( \varepsilon_0 \) and \( \mu_0 \) are the vacuum permittivity and permeability, \( \varepsilon' \) and \( \mu' \) are the real and imaginary parts of the substance permittivity and permeability, \( \varepsilon'' \) and \( \mu'' \) are their imaginary
parts. In order to find these values one should initially calculate the wave impedance $z$ (2) on the air-dielectric boundary [4,5].

$$z = \sqrt{(1 + S_{11})^2 - S_{21}^2 \over (1 - S_{11})^2 - S_{21}^2}$$

(2)

where $S_{11}$ and $S_{21}$ are $S$-parameters. Usually vector network analyzers can directly provide $S$-parameters. It is also important to take into account the phase factor $e^{\gamma d}$, which depends on the wave impedance (2):

$$e^{\gamma d} = 1 - S_{11}^2 + S_{21}^2 + 2 S_{11} \over 2 S_{21}$$

(3)

the value $\gamma$ is a propagation constant of a wave penetrating the sample, while $d$ is a sample thickness. In measurements one obtains a set of $S$-parameters for the whole measured frequency band. ($N$ values). The next step is the calculation of the complex argument $\phi_N$, which can be represented in the form (4):

$$\phi_N = \phi_0 + \sum_{i=1}^{N} \text{arg} \left( e^{\gamma d} \over e^{\gamma_{i-1} d} \right)$$

(4)

where $\phi_0$ is the phase at the first frequency. Finally the refraction coefficient can be calculated by means of the following formula (5):

$$n_N = \sqrt{1 \over (k_0 d)^2 (\omega_N - j \ln |e^{\gamma d}|)^2 - (\omega_c / \omega_N)^2}$$

(5)

where $\omega_c$ is the cutoff frequency of the measurement waveguide, $\omega_N$ is the angular frequency. The next step is to calculate the magnetic permeability $\mu$ and the dielectric permittivity $\epsilon$:

$$\hat{\mu} = z \over 1 - (\omega_c / \omega_N)^2$$

and

$$\hat{\epsilon} = n^2 \over \hat{\mu}$$

(6)
The formula (6) finally gives the parameters to be calculated $\varepsilon$ and $\mu$.

The important parameter in the S-parameter measurements is the phase delay of the wave propagation within the material sample. The phase delay introduces some limitations on the possible surface shape of the studied sample. Therefore it is important to ensure parallel-plate shape of the sample, which does not affect the phase of the wave. The liquid state samples are harder to control the phase while measurements. Therefore we have used films with known values of the dielectric permittivity as a function of frequency. Based on those values the additional phase delay was taken into account. Results of measurements are shown in Fig.3.

![Figure 3.](image)

**Figure 3.** The extraction of the real part of the permittivity (left axis) and its imaginary part (right axis) for a distilled water at 23 °C.

### 3. Active nearfield diagnostics

The method of the active nearfield diagnostics allows obtaining information about the permittivity value of a liquid and its conductivity in a broad frequency band. This method is based on the measurements of an impedance of an electrically small antenna located in the vicinity of the air-liquid interface [2]. In such a case the antenna impedance is determined not only radiative part like in free space, but also by additional terms due to quasistatic components of an electric field. Therefore the essential of the method is to analyze S-parameters by means of a vector network analyzer Rohde & Schwarz, which makes possible to calculate the antenna impedance. The principal difference in radiation of such an antenna in air from its radiation on the boundary of the liquid is the presence of the imaginary part of the dielectric permittivity, which makes a part of the energy absorbed. The most of electrically small antennas have dominating capacitive part of the impedance. Therefore the matching of such antennas is extremely sensitive to the imaginary part of the substance permittivity. Consequently the small change in the imaginary part of the permittivity affects the impedance and the resonance frequency. The value of this response allows determination of the material properties, which is a physical basis of the Active Nearfield Diagnostics method. Let us note that this method can be employed not only for pure substances (e.g. a distilled water) but also mixtures, solutes and suspensions. It is important because admixtures can considerably change the losses of the main substance. It results in a change of a skin depth from several millimeters to several centimeters.
on a broad frequency range. The measurements by this method include several steps. Firstly

one needs the information about the parameter dispersion of the calibrating liquid of a similar order of permittivity in the measured range. Thus one needs to have a prior information about the measured liquid. The second step is calibration of the whole system taking into account the effects of multiple reflections and losses in the feeding cables and connectors, the size of the probe antenna and the signal renormalization to the known material parameters of the calibrating liquid. The third step is the measurement process itself, which assumes positioning of the probe in the vicinity of the waver surface and obtaining S-parameters.

The experimental setup schematics is depicted in Fig.4. The electrically small antenna is located in air at some distance from the measured liquid’s surface. The antenna sizes and the distance to the liquid are much smaller than the wavelength. Results of measurements are shown in Fig.5. In addition to water properties it is important to measure properties of salt solutes. Water is one of the main components of live organisms. Salt solutes can be a first order approximation of the tissues. Results of measurements are shown in Fig.6, 7.

![Figure 4. Schematics of the experimental setup.](image)

**Figure 4.** Schematics of the experimental setup.

![Figure 5.](image)

**Figure 5.** The extraction of the real part of the permittivity (left axis) and its imaginary part (right axis) for a distilled water at 23 °C.
4. Conclusion
In this work the values of the real and imaginary parts of the permittivity and the conductivity of water and salt solutes were measured by means of two methods: the Nicolson-Ross-Weir method and the active nearfield diagnostics method.

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References
[1] Luukkonen O, Maslovski S I, Tretyakov S A 2011 A Stepwise NicolsonRossWeir-Based Material Parameter Extraction Method IEEE antennas and wireless propagation letters vol. 10 1295-1298
[2] Urasova N V 2006 The near-field UHF probing stratified medium Nizhniy Novgorod 113
[3] Samoilov V O 2004 Medical biophysics SpecLit 496
[4] Nicolson A M and Ross G F 1970 Measurement of the intrinsic properties of materials by time-domain techniques IEEE Trans. Instrum. Meas. 19 377-382
[5] Weir W B 1974 Automatic measurement of complex dielectric constant and permeability at microwave frequencies Proc. IEEE 62 33-36