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An electrodeless system for measurement of liquid sample dielectric properties in Radio Frequency band

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Abstract— **An electrodeless measurement system based on a resonant circuit is proposed for the measurement of dielectric properties of liquid samples at RF (Radio Frequency).**

Generally, properties as dielectric constant, loss factor and conductivity are measured by parallel plate capacitor cells: this method has several limitations in the case of particular liquid samples and in the range of radiofrequencies.

Our method is based on the measurements of resonance frequency and quality factor of a LC resonant circuit in different measuring conditions, without and with the liquid sample placed inside a test tube around which the home made coil is wrapped. The measurement is performed using a network analyzer and a dual loop probe, inductively coupled with the resonant circuit. One of the advantages of this method is the contactless between the liquid sample and the measurement electrodes. In this paper the measurement system is described and test measurements of conventional liquids dielectric properties are reported.

I. INTRODUCTION

Studies on the interaction between electromagnetic fields and biological tissues in the RF range involve the estimation of the exposure level for biological tissues. The term "dosimetry" indicates the estimation of the power deposition per mass unity in a biological sample (SAR: Specific Absorption Rate), due to the interaction with an electromagnetic field. For numerical dosimetry the dielectric properties, like dielectric constant, loss factor and conductivity, of each biological tissue are necessary [1][2]. Although many methods to measure complex permittivity of several substances are presented in literature [3], the dielectric properties are not clearly reported in the RF band and often the values don't agree each other. Moreover, in microbiological studies there is the need to perform dosimetry experiments on *in vitro* samples with unknown dielectric properties. For these reasons a robust and easy method to measure the properties of several substances is necessary.

A conventional method used to measure dielectric properties in the RF frequency is the parallel plate capacitor sample cell: this method implies the contact between the capacitor electrodes and the sample that could be influence the sample property values with the transfer of charges [4].

We developed a liquid sample dielectric properties measurement system based on the evaluation of the resonance frequency and quality factor of a resonant circuit composed by a home-made resonant coil. The major advantage of this method is the contactless between the liquid sample and the measurement electrode.

Another electrodeless measurement of RF dielectric properties is reported in literature in 1993 [5], but it is tested in the range of 2-20 MHz and it presents several differences with our novel technique.

Since final goal of our work is the estimation of the *in vitro* SAR value in a clinical Magnetic Resonance (MR) environment, our measurements are relative to the specific frequency of the RF magnetic field of this system.

II. METHODS

A. Dielectric Properties

The complex permittivity of a dielectric materials is expressed as:

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

The real part ε' of the complex permittivity is called dielectric constant or relative permittivity and it can be used to calculate the dielectric material impedance. The imaginary part $\varepsilon''$of the complex permittivity describes the energy loss from an electrical signal that passes through the dielectric.

The loss factor or loss tangent tan δ is defined as the ratio between the energy dissipated and the energy stored in the dielectric material:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (2)$$

The conductivity σ of a dielectric material can be defined as:

$$\sigma = \omega\varepsilon_0\varepsilon'' \qquad (3)$$

where ω is the angular frequency of the electrical signal.

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B. Measurement System

The measurement system is based on a coil that resonates at the frequency of interest. As our MR system have a static magnetic field of 1.5T, according to the Larmor's equation [6], the RF magnetic field involved in our application has a frequency of 63.85 MHz.

The designed coil is constituted by a home-made solenoid and a high quality capacitor, so the resonance frequency f_0 of this circuit is given by:

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_0}} \tag{4}$$

where L_0 is the inductance of the coil without any sample placed inside and C_0 is the capacitance value of the capacitor.

The coil is designed using a copper wire with a diameter of 1 mm wrapped 6 times around a cylindrical test tube with a radius of 14 mm. In order to tune the resonant circuit at a frequency of about 64 MHz, the capacitor C_0 must have a value of 5.6 pF.

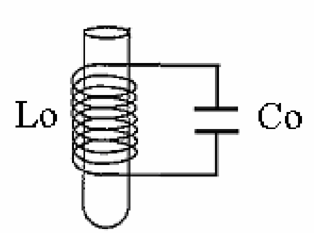

Fig. 1. Resonant circuit.

Expressing the energy losses of the coil by a resistor with a value of R_0, we can calculate the quality factor Q_0 of the resonant circuit, without any sample placed inside the test tube, by the following equation:

$$Q_0 = \frac{2\pi f_0 L_0}{R_0} = \frac{1}{2\pi f_0 C_0 R_0} \tag{5}$$

For the evaluation of the frequency and quality factor we employed a home-made dual-loop probe (Fig. 2), consisting of two mutually decoupled pickup loops, and a network analyzer HP3577 (Hewlett Packard). With this structure, the transmit loop couples weakly to the solenoid, which in turn is weakly coupled to the receive loop. The power transmitted from the transmit to the receive loop is proportional to the amplitude of the oscillation in the solenoid and therefore represents its frequency response.

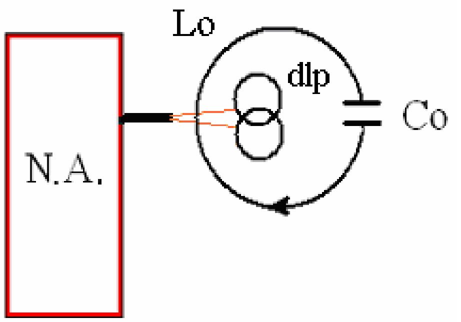

Fig. 2. Measurement system with resonant circuit, dual loop probe and network analyzer.

In the first experimental condition (coil unloaded), we measured with the network analyzer the resonance frequency f_0 and the -3dB band B_0, so we can calculate Q_0 as:

$$Q_0 = \frac{f_0}{B_0} \tag{6}$$

and it is possible to obtain R_0 value by (5).

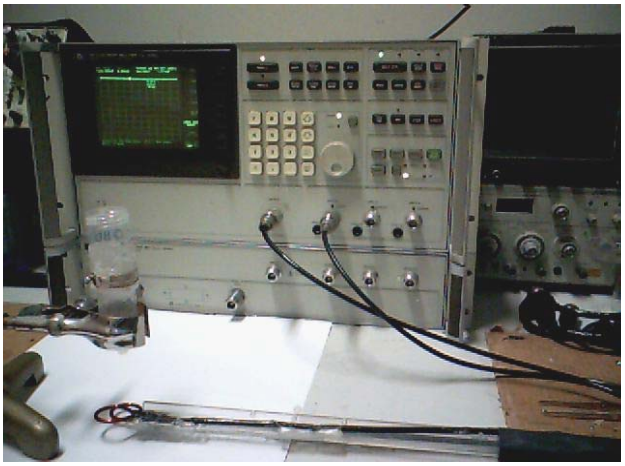

Fig. 3. Photograph of measurement system.

Afterwards, we spilled the liquid test sample inside the test tube; the new experimental condition can be schematized with the equivalent circuit in Fig. 4, where Cs and Rs are respectively the sample capacitance and resistance.

In this condition we measured the new resonance frequency f_0', the new -3dB band B_0', and we can calculate the new quality factor Q_0' using (6).

The new loss resistance R_0' is equal to the sum of the coil loss resistance R_0 and the sample resistance Rs, and the new capacitance C_0' is equal to the sum of C_0 and the sample capacitance Cs (in the circuital schematization these two capacitors are in parallel).

These parameters can be calculated by the following equations:

$$Q_0' = \frac{2\pi f_0' L_0}{R_0'} \tag{7}$$

$$f_0' = \frac{1}{2\pi\sqrt{L_0 C_0'}} \tag{8}$$

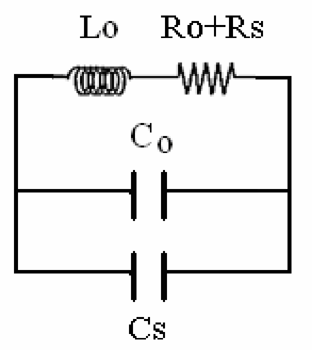

Fig. 4. Equivalent circuit with the liquid sample placed inside the coil.

So, the contributions of the sample can be calculated as follow:

$$Rs = R_0' - R_0 \tag{9}$$

$$Cs = C_0' - C_0 \tag{10}$$

Comparing this *Cs* value with those of standard dielectric samples with known ε' values, it is possible to evaluate the real part of the dielectric constant of the under test sample.

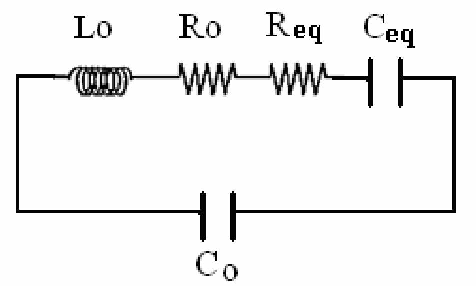

Fig. 5. Equivalent circuit with the series schematization of the dielectric sample.

It is possible to express the contributions of the sample as a series combination of a resistance *Req* and a capacitor *Ceq*, that can be calculated equalling the impedance value of the circuit in Fig. 4 with the impedance value of the circuit in Fig. 5.

We obtain:

$$R_{eq} = Rs \tag{11}$$

$$C_{eq} = \frac{-C_0\left(C_0 + Cs\right)}{C_s} \tag{12}$$

In this way, the sample contributions can be expressed by the sample impedance *Zsample* equal to:

$$Z_{sample} = R_{eq} - j\frac{1}{2\pi f_0' C_{eq}} \tag{13}$$

therefore, we can calculate the loss tangent by the definition [7]:

$$\tan\delta = -2\pi f_0' R_{eq} \cdot C_{eq} = \frac{\sigma}{2\pi f_0' \varepsilon_0 \varepsilon'} \tag{14}$$

from which it is possible to evaluate the conductivity σ of the liquid sample.

III. Experimental Results

In order to validate our method, we applied it to several standard dielectric liquid samples with known dielectric constant at frequency of interest (about 64 MHz) [8].

These samples were: distilled water (ε'= 78.5), formic acid (ε'=58), glycerol (ε'=42.5), methanol (ε'=33.1), ethanol (ε'=24.3), acetic acid (ε'=6.2), chloroform (ε'=4.8), sunflower oil (ε'=3.1), air (ε'=1).

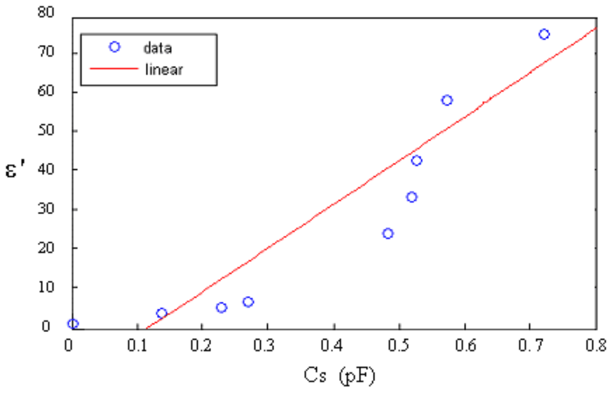

Fig. 6. Relationship between the measured capacitance Cs and the dielectric constant of tested samples.

Fig. 6 shows the measured capacitance values for each sample: it is possible to note a linear relationship between the Cs values and dielectric constants.

Measuring the values of *Cs* for a dielectric sample with unknown dielectric properties at the frequency of interest, and using this relationship, the dielectric constant can be evaluated.

Once calculated the dielectric constant and the loss tangent of the liquid sample under the test, it is possible to calculate the conductivity using (14). For some of standard dielectric samples we obtained the conductivity values reported in table 1, which correspond quite well to the literature values [8]. For the others tested dielectric materials we didn't find values reported in literature at frequency of 64 MHz, but only at different points in the RF range (i.e. 10-500 MHz), and the measured conductivities well agree with these values and their frequency patterns [9].

TABLE I
MEASURED CONDUCTIVITY VALUES

Dielectric sample	Conductivity (mS/m) at frequency of 64 MHz
Distilled water	2.038
Ethanol	1.280
Methanol	0.824
Sunflower oil	1.000
Glycerol	0.123

IV. DISCUSSION AND CONCLUSIONS

Several studies on the interaction between electromagnetic fields and biological tissues regard the radio frequency band: in our specific case, we are interested on measurement of power deposition per mass unity due to the RF field in which human body is immersed during a MR exam. This evaluation requires the calculation of the SAR that involves the knowledge of the biological tissue dielectric properties at the specific electromagnetic field frequency. For this reason we presented a method for the measuring of liquid sample dielectric properties at 64 MHz without any contacts between the measurement electrodes and the sample.

We described the used theory and the system that is based on a resonant LC circuit and a dual loop probe to measure the resonance frequency and quality factor by using a network analyzer. We tested the technique on several standard dielectric liquid samples in order to evaluate their dielectric constants and conductivity. A linear relationship between the sample capacitance measured by our technique and the dielectric constant is found. This experimental relationship can be used to calculate the unknown dielectric properties of a liquid sample at the frequency of interest: in our specific case this frequency is related to the static magnetic field value of our MR system, but this method can be used for measurements in the whole RF range, tuning the resonant circuit on the desired frequency.

The results reported here agree with the literature values found for some of the used dielectric samples. Considering the poor presence of data in literature at specific frequency in RF range and the disagree of the reported data, the presented method has a great relevance for studies that involve dielectric properties knowledge.

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