MEASUREMENTS OF COMPLEX PERMITTIVITY OF BIOLOGICAL AND ORGANIC LIQUIDS UP TO 110 GHZ

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ABSTRACT

A new procedure for measuring the complex permittivity of liquids has been set up. It is based on measuring the scattering parameters of waveguide two-ports, up to 110 GHz, and on an original calibration method previously developed by the authors. Measurements describe the complex permittivity of biological and organic liquids at frequencies above 20 GHz, up to 110 GHz. Comparisons with the well established Debye equations have been made and some parameters have been re-calculated when necessary.

INTRODUCTION

A good knowledge of the complex permittivity of biological media is necessary for determining adequately the action of electromagnetic fields, biological effects as well as medical applications. Hyperthermia is only one example. There is a lack however of data measured on biological and organic liquids at frequencies above 20 GHz. The paper presents original measurements on such liquids, at frequencies from 8 to 110 GHz, in five waveguide bands respectively. The liquids are methanol, dioxane, and blood. More measurements are presently being made.

The usual practice for liquids is to measure the reflection coefficient of an open-ended coaxial probe [1]. Two difficulties however are related to this practice, especially when applying in the high range of frequencies: the structure radiates, and the size of the coaxial probe is very small, hence the mechanical accuracy may not be good enough. We used a waveguide transmission method on a vector analyzer, yielding the four complex scattering parameters: reflection at both ends, and transmission in both ways. It has been shown by the authors [2] that, by using adequately a new wideband calibration method, called the LL method [3], the complex permittivity is obtained explicitely. The method hence avoids the difficulties related to the inversion of implicit expressions, in particular tedious numerical iterations.

Some interesting comparisons have been made between our fitted measurements and classical empirical equations [4] leading to the determination of complementary terms to those equation.

MEASUREMENT PROCEDURE

Figure 1 illustrates the measurement configuration. A waveguide spacer is placed between the two waveguide ends of the vector analyzer. The connection between the waveguides and both ends of the analyzer is made by coax-to-waveguide transitions, for each frequency band. For calibration purpose and for using the LL method, two waveguide spacers are necessary in each band, *identical* except for their thickness. The LL method requires indeed respectively a "short" and a "long" line. A synthetic film (Parafilm) is placed at both ends between waveguides and spacers, containing hence the liquid in a known volume. Reference planes are placed at both ends in the plane of each film. The LL method ensures that the transition flange/Parafilm/flange has no effect on the result, provided that this transition is reproducible when using both spacers. Simple configurations, commercially available, are adequate.

In practice, the Parafilm is put on both sides of the waveguide spacer and soldered to it. Holes are made in the film, at the location of the holes of the waveguide flanges, to ensure tightness. Then, using a syringe, the liquid is inserted into the spacer. Air bubbles must be avoided. The two waveguides are then screwed together, through the holes of the spacer. This operation is done for each of the two spacers, for each waveguide band.

There are several advantages to this procedure. First, the test cell is made of devices commercially available. Second, only two operations are needed to extract the required experimental data, and explicit expressions provide the values of the complex permittivity. This is especially helpful for characterizing highly dispersive and lossy substances. Finally, the influence of the air-liquid interface is removed from the procedure, so that mismatch, radiation, and higher-order mode generation have no significant influence on the result.

RESULTS

The well-known first order Debye's equation is used to describe the variations of complex permittivities of substances as follows:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + j\omega\tau} \qquad (1)$$

where ε is the complex permittivity
ε_∞ is the permittivity at infinite frequency
ε_S is the static permittivity
τ is the relaxation time

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τ depends on the physical process involved. It can be as short as picoseconds (for reorientation of molecular dipoles) or as long as seconds (for counterion effects).

Few substances have a single relaxation time. For some materials (like water), permittivity is closely fitted by a first order Debye's equation, while for others (like biological media) where several relaxations are involved, higher orders terms are necessary [5]. Debye's equation can then be rewritten as:

$$\varepsilon = \varepsilon_\infty + \sum_{i=1}^{n} \frac{\Delta\varepsilon_i}{1 + j\omega\tau_i} \qquad (2)$$

where τ_i are several relaxation times due to several relaxation processes

$\Delta\varepsilon_i$ is the change of relative permittivity due to the dispersion associated with τ_i

Other empirical distribution functions have been widely used. One of the most known is Cole-Cole's equation [4] given by:

$$\varepsilon = \varepsilon_\infty + \sum_{i=1}^{n} \frac{\Delta\varepsilon_i}{1 + (j\omega\tau_i)^{1-\alpha_i}} \qquad (3)$$

where the α_i's correspond to measures of the broadening of the dispersion.

Table 1 summarizes the Debye's parameters used for comparison with our measurements. All the measurements have been fitted by using a least squared approximation with the MATLAB software.

Fig. 2 shows the value of dioxane ($C_4H_8O_2$) measured between 50 and 100 GHz. Only the real part of relative permittivity is presented. The imaginary value indeed is totally negligible. This shows that dioxane is a lossless dielectric up to 100 GHz. Fig. 3 shows the real and imaginary parts of the relative permittivity of methanol (CH_3OH), respectively, from 8.2 to 110 GHz. Measurements in the frequency band 12-18 GHz are presently missing. In Fig. 4 are presented the real and imaginary parts of the complex permittivity of blood, respectively, from 8 to 110 GHz. The blood is from beef, obtained in the morning of the day where the measurements were made. To avoid coagulation, heparin was added immediately after obtention (dosis: 0.2 mg/ml). The blood was refrigerated, and regularly stirred. When starting the measurements, blood temperature was 13°C. After preparation and during measurements, blood temperature reached an estimated temperature of 20°C.

DIOXANE

Our measurements (Fig. 2) complement results published earlier up to 20 GHz [1], showing that the dielectric constant dioxane is of the order of 2.25. This agrees well with the theoretical value in Table 1. Dioxane may hence be considered as a calibration dielectric.

METHANOL

The two dashdotted curves result from Debye's equation (Fig. 3). We note a discrepancy between Debye and the measurements, which is visible in the high frequency range, above 20 GHz. Those results complement results shown in Table 1. Two more relaxation times are necessary to fit the measurements curves. The time $\tau_2 = 6.2\ 10^{-12}$ s corresponds to the β-dispersion. The third time $\tau_3 = 1.95\ 10^{-12}$ s is rather unprecise.

BLOOD

Our new measurements follow well Debye's law, based on earlier published results at microwave frequencies, up to 20 GHz (dashdotted curves in Fig. 4), despite a possible temperature effect [6,7]. Taking those temperature differences into account new parameters have been calculated and are shown in Table 2. The dielectric properties of blood seem to be dominated by the dipolar relaxation of water at microwaves and millimeter-wave frequencies (Fig. 5).

All α_i's appear to be zero, possibly because of the low temperature.

CONCLUSIONS

A new procedure for measuring the complex permittivity of liquids has been set up. It is based on the measurement of scattering parameters of waveguide two-ports containing liquids, using a vector analyzer up to 110 GHz, and on an original LL calibration and measurement method previously developed by the authors. New measurements describe for the first time the complex permittivity of biological and organic liquids at frequencies above 20 GHz, up to 110 GHz. Other measurements are presently being made, including on axoplasm.

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	ε_∞	$\Delta\varepsilon_1$	τ_1 (ps)	α_1	$\Delta\varepsilon_2$	τ_2 (ns)	α_2	ref.
dioxane (25°C)	2.2	-	-	-	-	-	-	[1]
methanol (25°C)	5.6	27	48	-	-	-	-	[1]
blood (human) (25°C)	4.5	51.1	8 4	-	-	-	-	[6]
(37°C)	4.0	56	8.38	0.1	5200	132.63	0.1	[7]

Table 1. Parameters from the litterature for the Debye's or Cole-Cole's equations

	ε_∞	$\Delta\varepsilon_1$	τ_1 (ps)	$\Delta\varepsilon_2$	τ_2 (ps)	$\Delta\varepsilon_2$	τ_3 (ps)
methanol (20°C)	4.5	29.1	48	0 9	6.2	0.2	1.95
blood (beef) (<20°C)	4	74.5	8.4				

Table 2. Parameters calculated from measurements (from 8 to 110 GHz)

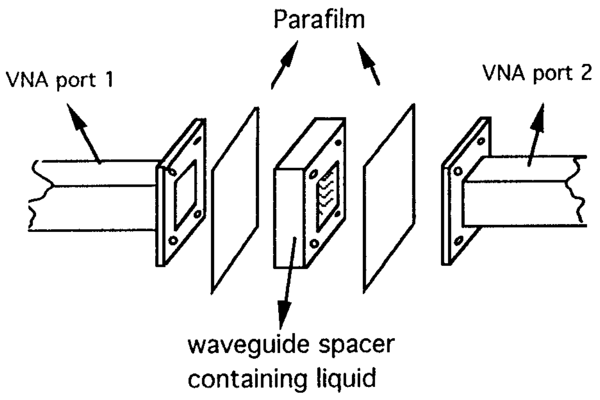

Figure 1. Measurement configuration

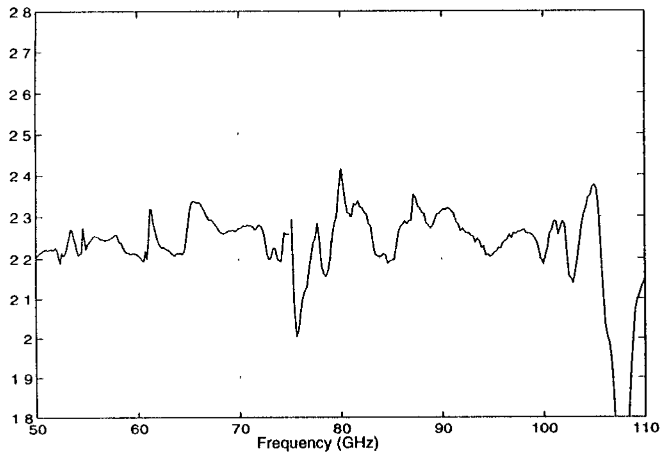

Figure 2. Real part of relative permittivity of dioxane

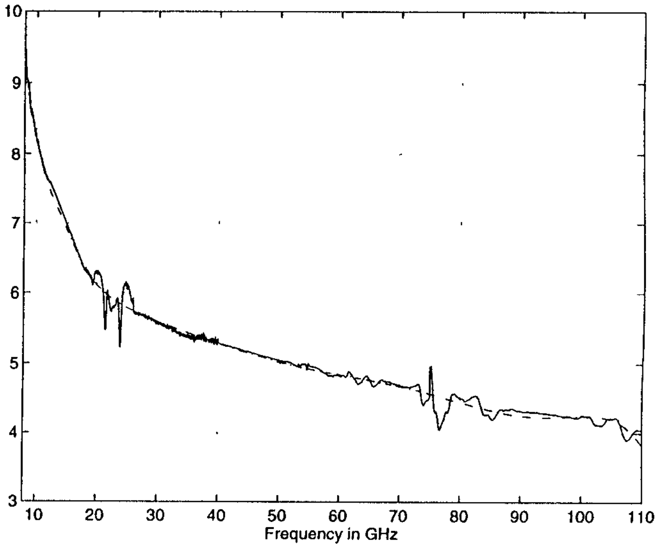

Figure 3.a Real part of relative permittivity of methanol
Solid line: measurements
Dashdotted line: fitted values (least-squared method)

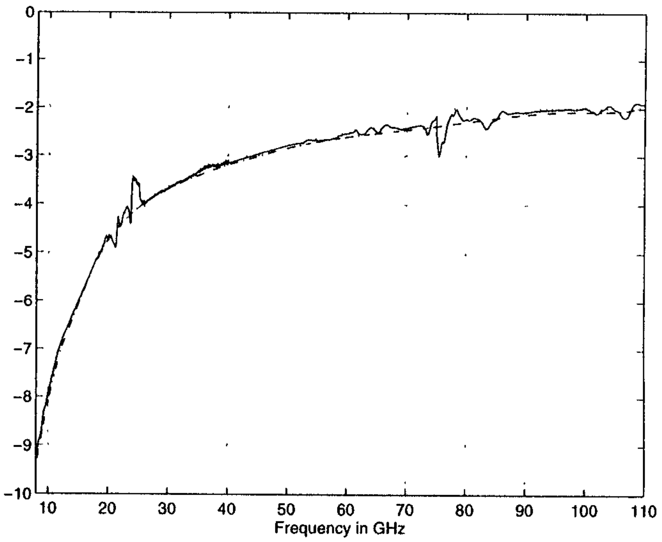

Figure 3.b Imaginary part of relative permittivity of methanol
Solid line: measurements
Dashdotted line: fitted values (least-squared method)

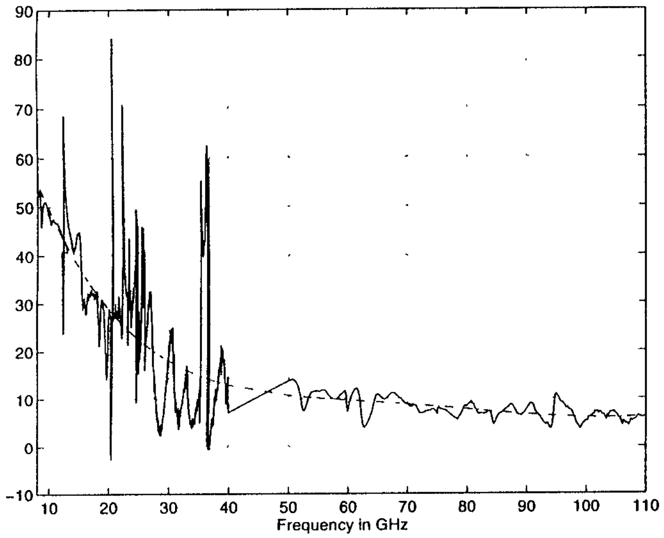

Figure 4.a Real part of relative permittivity of beef blood
Solid line: measurements
Dashdotted line: fitted values (least-squared method)

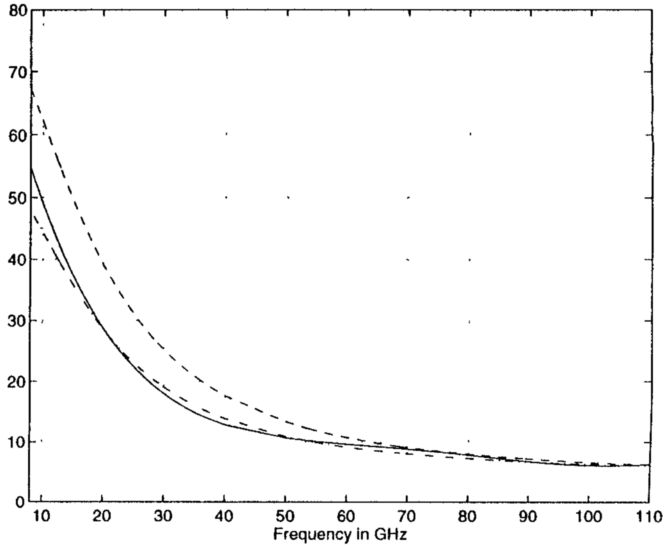

Figure 5.a Real part of relative permittivity of beef blood
Solid line: fitted values from measurements
Dashdotted line: first-order Debye's equation [6] or second-order Debye's equation [7]
Dotted line: new calculated Debye's equation with one relaxation time

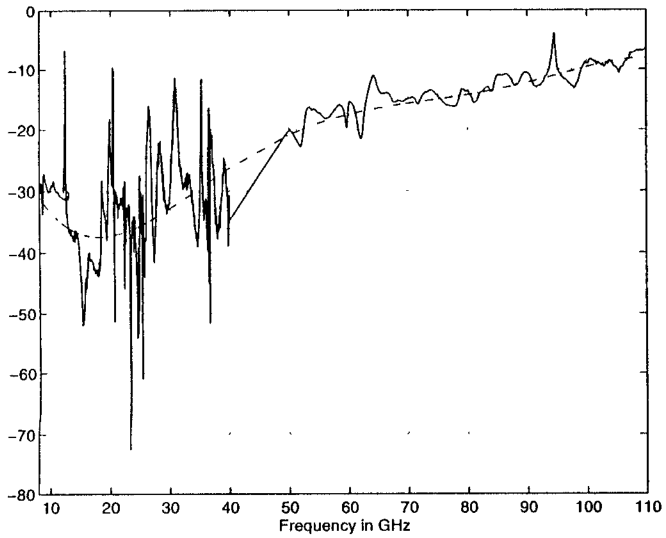

Figure 4.b Imaginary part of relative permittivity of beef blood
Solid line: measurements
Dashdotted line: fitted values (least-squared method)

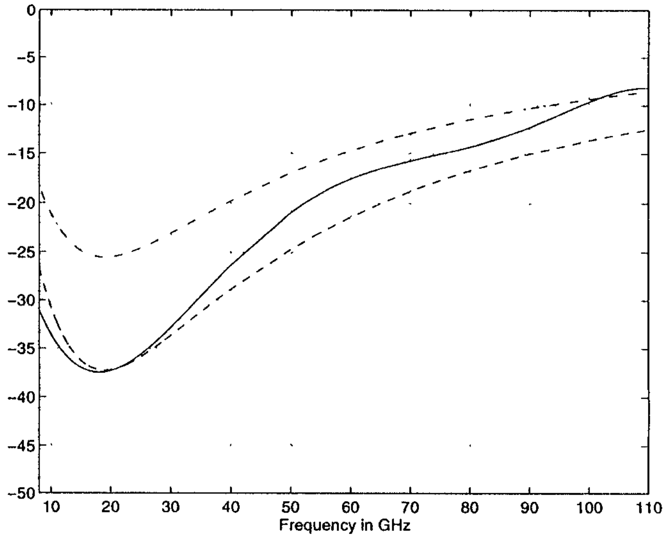

Figure 5.b Imaginary part of relative permittivity of beef blood
Solid line: fitted values from measurements
Dashdotted line: first-order Debye's equation [6] or second-order Debye's equation [7]
Dotted line: new calculated Debye's equation with one relaxation time