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Measurements of Dielectric Properties of Materials with High Water Content at Millimeter Waves using a Reverberation Chamber

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SHORT ABSTRACT

This study aims at introducing a method for determining the dielectric properties of lossy materials with high water contents in a millimetre-wave reverberation chamber. Such materials with high water content, *e.g.* biological tissues can be described by a Debye model. The proposed method consists in fitting the theoretical average absorption cross section to the experiment data resulting from the average absorption cross section measurements. By applying this method on a 4% agar phantom in the 50-65 GHz frequency range, it is demonstrated that the permittivity and conductivity of biological tissues can be determined at millimeter waves using reverberation chamber. The difference between the measured real and imaginary parts and the reference value of the agar phantom is 4.3% and 8%, respectively.

INTRODUCTION

A plethora of applications are under development at millimeter waves in the 30-100 GHz, like high speed point-to-point to point-to-multi-point indoor or outdoor communications. Particularly, recent progress in millimetre-wave wireless body-centric applications and commercialization of the new generation high-data rate wireless communication system in the 60-GHz band raise questions about potential health effects. Knowledge of dielectric properties of biological tissues is essential for evaluation of power absorption, specific absorption rate computation, numerical modelling and development of experimental phantoms.

Nowadays, several techniques are used to assess the complex permittivity of biological tissues: open-ended coaxial probe, reflection and transmission free space measurements, heating kinetics [1], etc. In this study, the proposed method to assess the complex permittivity of material sample is based on reverberation chamber (RC). RCs have been used in the past to determine the dielectric properties of phantom, but only in specific cases e.g. for low loss foams [2]. The average absorption cross section which depends on dielectric parameters, dimensions and shape is, in most cases, the parameter measured in RC to characterize dielectric samples. We consider here Debye model [3], valid only for materials with high water content, and the measured average absorption cross section (AACS) is used to assess the complex permittivity of the material under test. A simple phantom constituted of distilled water and agar with a concentration of 4 % is used to demonstrate the relevance and accuracy of the proposed method.

MATERIALS AND METHODS

Average absorption cross section computation

In general, the AACS is used in RC to quantify losses in dielectric objects. It represents the area which multiplied by the incident power density gives the power absorbed by the object [4]. The AACS of a parallelepiped lossy object is given in [5]

$$AACS_{theo} \approx \bar{T} \times S / 2 \qquad \textbf{(1)}$$

where S represents the physical area of the object. Equation (1) is only valid for skin depth smaller than the smallest size of the parallelepiped piece of material. The parameter T is the average plane wave transmission coefficient which depends on the incident angle and the electrical parameters and is computed by averaging the transmission coefficient over all angles of incidence θ, and polarizations H and V:

$$\bar{T} = 2\int_0^{\pi/2}\left[1 - \frac{\left|\Gamma_{TM}(\theta)\right|^2 + \left|\Gamma_{TE}(\theta)\right|^2}{2}\right]\cos\theta\sin\theta d\theta. \qquad \textbf{(2)}$$

In equation (2) $\Gamma_{TE}(\theta)$ and $\Gamma_{TM}(\theta)$ denote the transverse electric and transverse magnetic plane wave Fresnel reflection coefficients [6] which also depend on material properties, polarization, angles of incidence and frequency. Besides, for spherical objects the formulation of the absorption cross section is given in [7].

Several measurement techniques can be used to evaluate the AACS in RCs. Generally, the AACS is determined from the measurements of the power transfer function between two antennas placed inside the RC, with and without the object [8]. However, in this study, the AACS is computed from the estimation of the coherence bandwidth of the loaded and empty RC [5]

$$AACS_{mes} = \frac{V\pi\sqrt{3}}{c}\left(CB_L^{cpx,0.7} - CB_E^{cpx,0.7}\right), \qquad \textbf{(3)}$$

where V is the chamber volume, c the speed of light, $CB^{\mathrm{cpx},0.7}$ is the average coherence bandwidth computed from the complex transfer function of the RC at a correlation level of 0.7.

Proposed method

The relaxation frequencies of material with high water content, including biological tissues, are very close to the relaxation frequency of free water. Consequently, the dielectric parameters at millimeter waves for this kind of materials can be described by a Debye model [3]

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{\Delta\varepsilon}{1 + j2\pi f\tau} + \frac{\sigma_i}{j\omega\varepsilon_0}, \qquad \textbf{(4)}$$

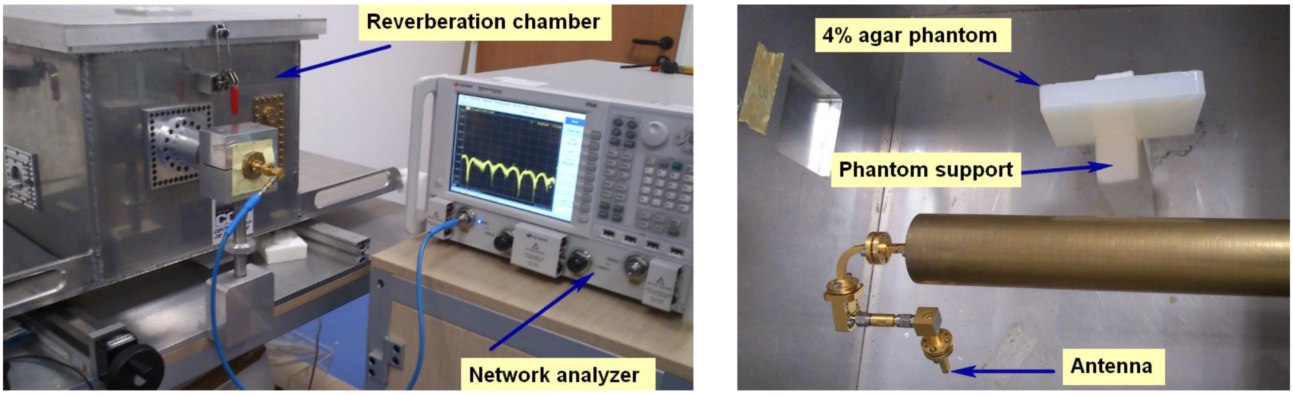
where τ is the relaxation time, $\Delta\varepsilon = \varepsilon_\infty - \varepsilon_s$ is the magnitude of the dispersion, ε_s is the static permittivity, ε_∞ is the optical permittivity, $\varepsilon_0 = 8.85 \times 10^{12}$ F/m, σ_i is the ionic conductivity and f is the frequency. The relaxation time is that of free water and the optical permittivity ε_∞ equals to 2.5 +2.7*Wt*, where *Wt* is the weight fraction of the total water content of the material to be characterized [1, 9**]**. In summary, the only unknown parameter is the magnitude of the dispersion $\Delta\varepsilon$, since the ionic conductivity $\sigma_i = 0$ if the material is constituted of distilled water.

The proposed method consists in fitting the theoretical values of the average absorption cross section (or the average power transmission coefficient) to the experimental ones by varying the magnitude of the dispersion $\Delta\varepsilon$. The complex permittivity of the material is obtained with the optimal value of $\Delta\varepsilon$ giving the best fit of the experimental data.

A specific phantom constituted of distilled water with a concentration of 4% of agar is used here. The phantom shape is parallelepiped and its dimensions are 9.9 × 9.9 × 1.4 cm^3.

Experimental set-up

The experimental set-up is presented in Figure 1. Measurements were performed in a small RC built-up for millimetre-wave applications, its dimensions are 0.423 × 0.412 ×0.383 m^3. It was demonstrated in [10] that the statistical behaviour of the experimental electromagnetic field inside the chamber, in the 58.5–61.5 GHz range, is consistent with that of a classical RC. The agar phantom was placed close to the middle of the RC on a low-loss foam support (Rohacell 51 HF, $\varepsilon_r \sim 1.05$). A WR-15 open-ended waveguide was used simultaneously as a transmitting and a receiving antenna. Measurements were performed with a vector network analyzer.



a) Ouside view

b) Inside view

Figure 1: Experimental set-up used for S-parameter measurements: (a) outside and (b) inside views.

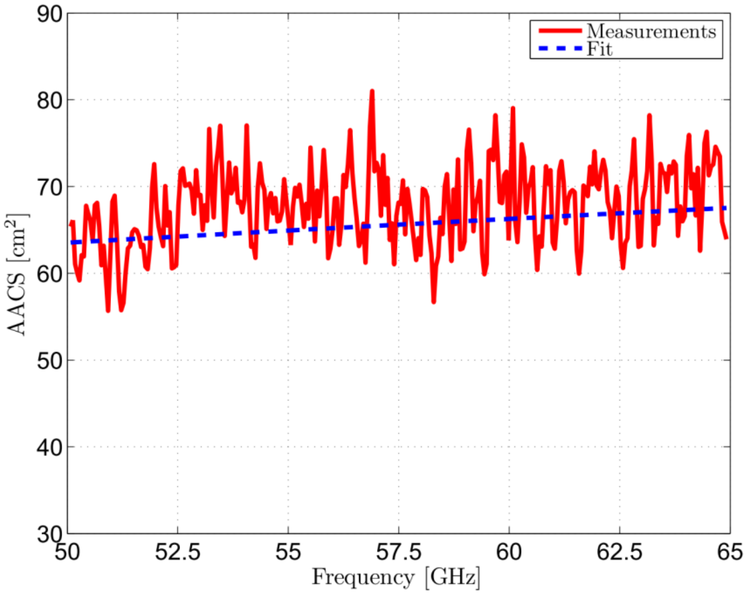


Figure 2: The experimental average absorption cross section fitted with the theoretical model.

RESULTS

Scattering parameters were measured in the 50-65 GHz frequency range with a frequency resolution of 600 kHz. By moving the antenna inside the RC, P = 51 positions of the antenna were considered. The distance between two successive positions of the antenna was 5 mm. From the 51 values of measured reflection coefficients S_{11}, the average transfer function of the antenna was estimated over the P positions [11]. Next, the coherence bandwidths were computed in sub-bandwidths of Δf = 150 MHz with a step between two consecutive estimation of 50 MHz. Figure 2 shows the experimental AACS with respect to frequency. Fluctuations in the experimental curve is likely due to the limited number of realization s. Moreover, this estimation comes from the difference of two coherence bandwidth estimations. In order to assess the complex permittivity from the measurements, the procedure consists of seeking the value of $\Delta\varepsilon$ by least-squares technique (see Figure 2 for the fitting). The resulting value of $\Delta\varepsilon$ was used in equation (4) to compute the real and imaginary part of ε^*. Results are provided in Figure 3. The difference between the measured real and imaginary parts and the reference value of the agar phantom is 4.3% and 8%, respectively. The method accuracy depends on the uncertainties of the coherence bandwidths determination. This could be improved by increasing the number of realizations and by performing the measurements with a smaller frequency resolution.

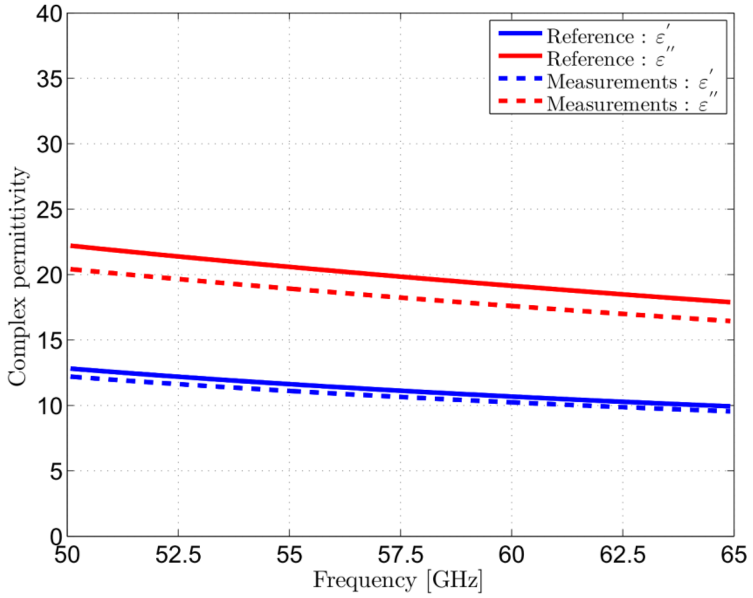


Figure 3: Complex permittivity of the agar phantom compared to the measured one.

CONCLUSIONS

We have provided a method using the average cross section measurements and the Debye model in order to determine the complex permittivity of material with high water content at millimeter waves. This method has some advantages compared to the most common methods for characterization of materials. Non-invasive measurements are allowed by this technique. In addition, it is a broadband method and easy for implementation. This method can be used to characterize homogenous biological tissues and phantoms with tissue-equivalent dielectric properties.

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