A Dispersion Modeling Approach for Designing Broadband Tissue-Simulating Fluids

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***Abstract*—Fluids with dielectric properties meeting SAR measurement standard requirements over a broad frequency range are of particular interest for the wireless industry. This paper introduces an analytical model suitable for describing frequency dispersion of normative target permittivity and conductivity from 30 MHz up to 6 GHz. The proposed model allows easier interpretation of physical mechanisms to involve in a chemical system meeting standard requirements. It also provides significant help in designing broadband tissue-simulating materials.**

Keywords—SAR measurement; tissue-simulating material; dielectric properties

I. INTRODUCTION

Specific Absorption Rate (SAR) is known as the relevant quantity for evaluating exposure to radiofrequency electromagnetic (EM) fields radiated by a wireless device held in close proximity to the user. International guidelines / standards [1], [2] define limits for peak spatial-average SAR and measurement standards describe protocols for assessing this quantity [3]-[5]. Standard methods are widely accepted and recognized by national regulators as appropriate approaches to demonstrate compliance of handheld and body-worn devices with applicable exposure limits.

SAR evaluation is performed using head or body mannequins (phantoms) consisting of a plastic shell filled with homogeneous tissue-simulating fluid. Target dielectric properties of such fluid have been designed to ensure a conservative estimate of SAR for a significant majority of exposure conditions. Numerical EM simulations [6], [7] were used as a basis to derive permittivity and conductivity specifications across the 30 MHz to 6 GHz frequency range. Target values hence do not result from dielectric properties of a particular biological tissue or any existing system. A practical consequence of this is that most of the tissue-simulating materials available can only meet standard requirements over a relatively narrow frequency band. Recently a few groups have proposed simulants covering wider frequency ranges [8], [9]. Broadband fluids however generally suffer of instability, resulting in a rapid degradation of performances over time.

In [10], the authors have reported on a new methodology allowing the design of a liquid capable of meeting standard requirements over a frequency decade or more with a significantly increased time-stability. This paper gives more details about this specific methodology. In particular, it shows the interest of analyzing and modeling frequency dispersion of target dielectric properties in identifying relevant physical chemical phenomena to be considered for deriving a targeted wideband solution.

II. ANALYSIS AND MODELING OF TARGET PROPERTIES

The complex permittivity ε* of a dielectric medium can be written as:

$$\varepsilon^*(\omega) = \varepsilon'(\omega) + j(\varepsilon''(\omega) - \frac{\sigma_S}{\omega\varepsilon_0}) \tag{1}$$

Where ε' is the relative permittivity of the medium, ε'' is related to dielectric losses, σ_S is the static conductivity in $S.m^{-1}$.

Standardized target dielectric properties [5] for fluids used in SAR measurement are summarized in Table I. Fig. 1 represents the frequency dispersion of ε' and ε'' for those targets. Permittivity and conductivity at frequencies in-between the points listed in Table 1 are obtained by linear interpolation. Values at frequencies up to 6 GHz are obtained from linear extrapolation based on data at 3 and 5.8 GHz points. By observing the shape of the represented curves on Fig. 1, three particular points can be noticed:

- The linear decrease of ε'' at lowest frequencies is typical of systems involving an ionic conduction phenomenon.
- The inflexion of the ε'' curve at 300 MHz could be achieved from a polarization phenomenon.
- A dipolar relaxation at frequencies around 7 or 8 GHz would allow to tune the profile of ε'' slope between 3 and 6 GHz as shown on Fig. 1.

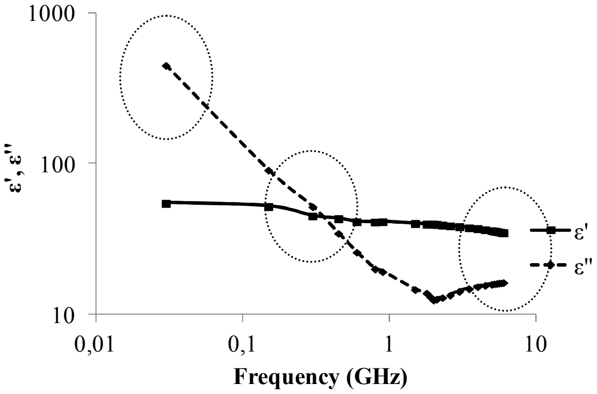

Fig. 1. Frequency dispersion of IEC target dielectric properties

As a consequence, a chemical system designed and optimized to exhibit the above-described three mechanisms would provide a solution for meeting standard requirements over a wide frequency range.

TABLE I. IEC 62209-2 TARGET DIELECTRIC PROPERTIES [5]

Frequency (MHz)	Relative permittivity	Conductivity ($S.m^{-1}$)
30	55.0	0.75
300	45.3	0.87
450	43.5	0.87
835	41.5	0.90
900	41.5	0.97
1450	40.5	1.20
1800	40.0	1.40
1900	40.0	1.40
2000	40.0	1.40
2450	39.2	1.80
3000	38.5	2.40
5800	35.3	5.27

From an analytical viewpoint, the complex permittivity of a system involving such phenomena can be written as a function of frequency, as follows [11]-[12]:

$$\varepsilon^* = \varepsilon_\infty + \frac{\sigma_s}{j\omega\varepsilon_0} + \frac{\Delta\varepsilon_1}{[1+(j\omega\tau_1)^{\beta_1}]^{\alpha_1}} + \frac{\Delta\varepsilon_2}{[1+(j\omega\tau_2)^{\beta_2}]^{\alpha_2}} \quad (2)$$

Table II shows the obtained parameters for Eq. 2 allowing accurate fitting between the analytical dispersion model and IEC 62209-2 requirements. Relaxation frequencies f_1 and f_2 correspond to the inverse of relaxation times τ_1 and τ_2, respectively. $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ represent the strength of the dielectric dispersion.

TABLE II. PARAMETERS OF EQ. 2 TO FIT THE MODEL WITH IEC 62209-2 TARGET DIELECTRIC PROPERTIES [5]

ε_∞	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	f_1 *MHz*	f_2 *MHz*	α_1	β_1	α_2	β_2	σ_s $S.m^{-1}$
4	12	28	200	7500	1	1	0.8	1	0.75

Fig. 2 illustrates the fit between the analytical model and IEC target dielectric properties over the 30 to 6000 MHz range. The good agreement obtained between the model and target properties confirms that a chemical system exhibiting ionic conduction and two well-tuned polarization phenomena could be suitable as a broadband tissue-simulating material.

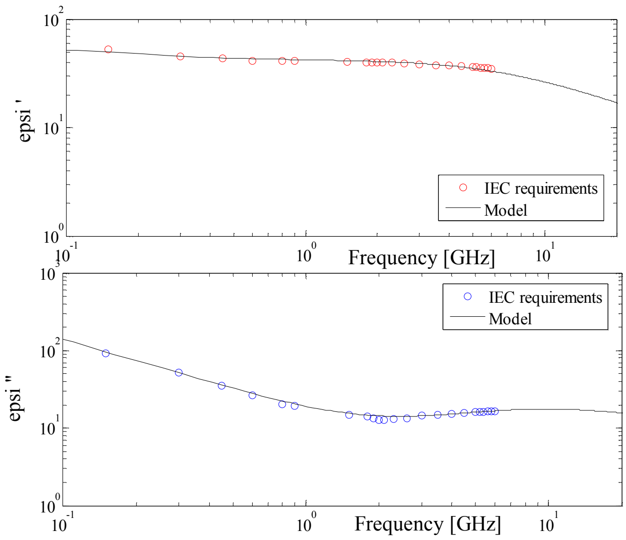

Fig. 2. ε' and ε'' as functions of frequency: analytical model fit with IEC 62209-2 dielectric requirements [5]

III. BROADBAND FLUID DESIGN

A. Design strategy

In order to design a chemical system involving the previously discussed mechanisms, water-based emulsions appeared to be excellent candidates. Indeed, such systems combine the properties of several dielectric materials, including free and bound water. Interfacial polarization, also known as the Maxwell-Wagner effect, can thus be generated [13]. Ionic conduction / static conductivity σ_S is tuned by adjusting the salinity of the solution. The higher frequency dipolar relaxation can be obtained from dipoles induced by hydrogen bonds between water molecules and an appropriate surfactant.

B. Materials and Methods

Based on this rationale, a direct emulsion – oil-in-water emulsion - has been formulated. Emulsification is carried out by using a propeller-type variable-speed stirrer. Each component is weighted and the dispersed phase is introduced into the continuous phase under mechanical stirring. Process parameters (stirring type, rotation speed, mixing time, temperature) have been optimized for providing optimal stability. Colloidal stability was estimated (1) visually as the time before phase separation occurs and (2) by measuring the evolution of dielectric properties over time.

Measurements were carried out at 23°C using a 85070E open-ended coaxial probe from Agilent Technologies.

C. Results

A broadband tissue-simulating material was thus developed. This new material appears stable for several months to more than one year, depending on the manipulation and storage conditions.

Measurements of dielectric characteristics show that this fluid meets IEC and IEEE standard requirements [3], [5] in the 600 to 6000 MHz range with a tolerance of ±10%. The results are represented in Fig. 3.

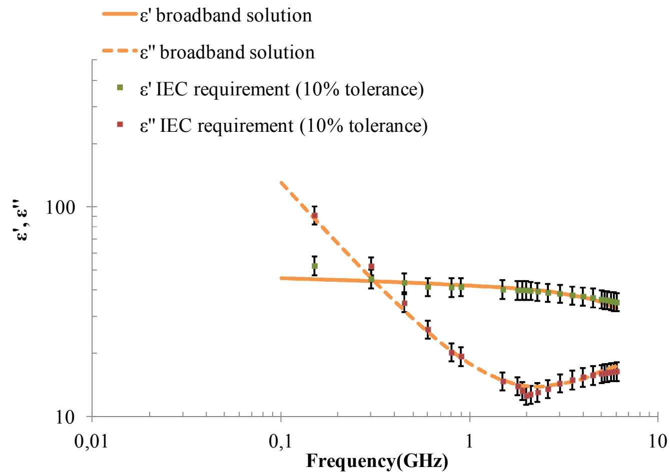

Fig. 3. Measured dielectric properties of the designed broadband solution between 100 and 6000 MHz

Table III gives the values of Eq. 2 parameters to best fit measured properties of the designed broadband tissue material. Comparison between Table II and Table III shows very similar values, except for f_1 being higher in the synthesized system and $_1$ being much smaller in the synthesized system, indicating that Maxwell-Wagner-type polarization needs to be emphasized for meeting perfectly standard requirements, especially for permittivity at frequencies lower than 300 MHz.

TABLE III. PARAMETERS OF EQ. 2 TO FIT THE MODEL WITH PROPERTIES OF DEVELOPED BROADBAND TISSUE-SIMULATING MATERIAL [5]

ε_∞	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	f_1 *MHz*	f_2 *MHz*	α_1	β_1	α_2	β_2	σ_s *$S.m^{-1}$*
4	6	30	380	7400	1	0.60	0.79	1	0.72

IV. CONCLUSION

A new dispersion model for SAR measurement standard dielectric requirements was introduced. This model proved to be useful in order to identify three relevant physico-chemical mechanisms. Such mechanisms need to occur in the fluid in order to achieve normative target properties over a wide frequency range. Measurement results for an emulsion exhibiting such phenomena were provided and demonstrated a match with standard requirements for permittivity and conductivity over more than a frequency decade. The presented approach is simple and shows potential to be applied to other applications where specific dielectric properties are supposed to be achieved over a broad range of frequencies.

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