Comparative Study of the Teflon® Electromagnetic Parameters (Permittivity and Permeability) Experimentally Obtained and Numerically Simulated

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Abstract— **The present report branches out into two related topics. The first is concerned with the implementation of a computational modeling to predict the behavior of electromagnetic materials in confined environment by using electromagnetic three-dimensional simulation. The second topic re-examines the Nicolson-Ross-Weir mathematical model to retrieve the constitutive parameters (complex permittivity and permeability) of a Teflon® sample from the measurement of scattering coefficients. Recognizing the importance of this issue for the development of radar absorbing materials (RAMs), the present study contributes for the characterization of electromagnetic materials and, consequently, for the processing of RAMs in the microwave range.**

Keywords – electric permittivity; magnetic permeability; radar absorbing material; computational modeling

I. INTRODUCTION

Knowledge of complex permittivity, ε*, and permeability, μ*, of materials proves to be of great interest in scientific and industrial applications. Measurement of ε* and μ* in the microwave frequency range finds direct application, for instance, in the study of biological effects of electromagnetic radiation, in ceramic sintering, plastic welding, and remote sensing [1]. In fact, the dielectric constant of vegetation has a direct effect on radar backscattering measured by space-airbone microwave sensors. A good understanding of the dielectric properties of vegetation leaves is vital for extraction of useful information from the remotely sensed data for earth resources monitoring and management. Concerning sectors of electronic, telecommunication, aerospace industries, and in particular in the research and development of RAMs, the knowledge of ε* and μ* allows to predict the electromagnetic properties of materials via computer simulation to optimize the development and processing of new composites as well as their utilization for specific purposes.

Computational modeling becomes relevant as long as the simulated results reproduce and anticipate measured data. Strong interrelation between modeling and experiment contributes to ensure confidence in the computational tool developed for a given application. It is a purpose of computer modeling to reconstruct experimental measurements aiming at the understanding and evaluation of measured parameters, and also to obtain new parameters in different contexts but consistent with experimental interpretation. In situations in which a modal analysis turns out too complex and difficult to solve, numerical methods are widely used, such as finite element method (FEM), finite difference method (FDM), and particularly specialists tools for three-dimensional electromagnetic simulation in both time and frequency domain on volume and surface meshes. In this latter case, it can be mentioned the CST Microwave Studio, which is used for simulation the perfect boundary approximation (PBA) and the thin sheet technique (TST) to increase modeling precision in comparison with conventional software [2].

The present work makes use of the MS-CST to simulate the scattering parameters S11 and S21 of a Teflon® (polydifluoroethylene) test sample and then compare such frequency-dependent quantities with experimentally measured values in the 8.2-12.4 GHz frequency range (X band). From the magnitude and phase values of the simulated parameters, the Nicolson-Ross-Weir (NRW) method [3] is then applied to obtain the complex permittivity and permeability for a Teflon® test sample with 5.75 mm thickness.

To this end, we assembled a setup including an automatic vector network analyzer (VNA) HP8510C connected with a source and a measurement equipment. At the moment of calibration, standard setup values should be stored and compared to the measured values, in order to calculate systematic errors of the measurements. The calibration also establishes the reference planes for the measurement test ports. In Fig. 1 is shown the calibration X-band kit [4] used in this work. Fig. 2 sohws the used setup for the S parameters measurements. Fig. 3 presents the configuration modeling of electric and magnetic fields in X-band rectangular waveguide used.

Figure 1. Waveguide calibration set for X band .

Figure 2. S parameters measurements setup used. .

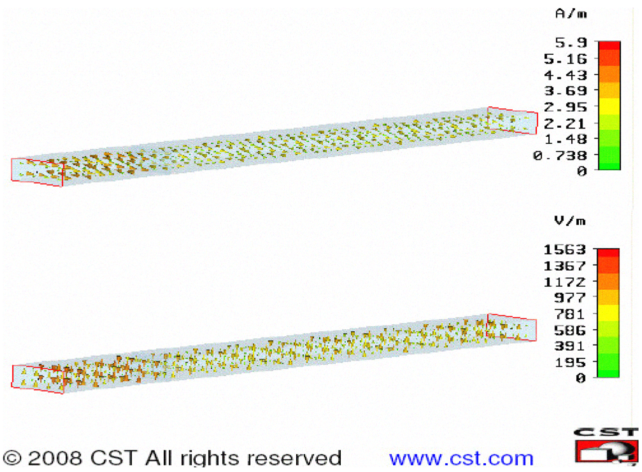

Figure 3. Configuration modeling of electric and magnetic fields in X-band rectangular waveguide.

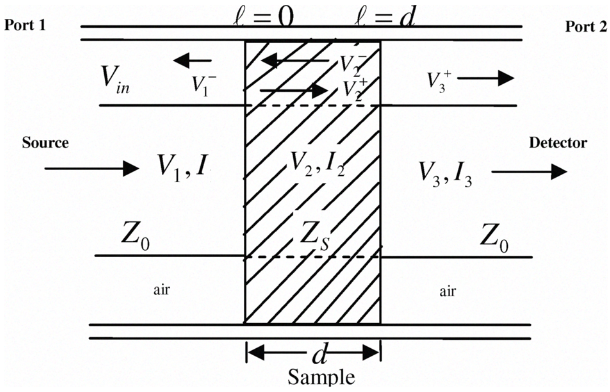

Figure 4. Line of air filled with material.

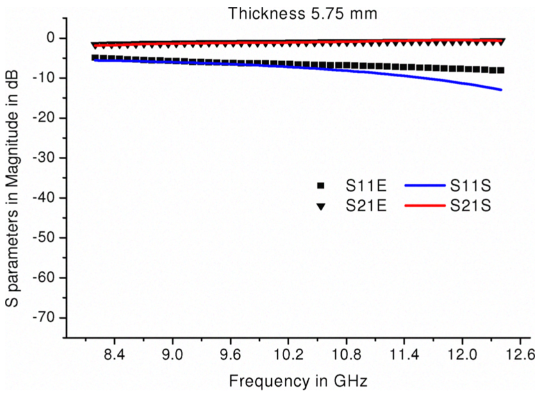

Figure 5. Experimental and simulated parameters of S11 and S21 of polydifluoroethylene with 5.75 mm of thickness.

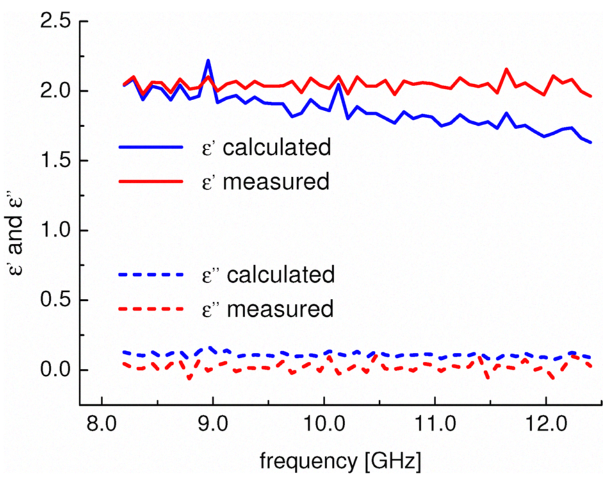

Figure 6. Test sample complex permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$: measured (red curves) and calculated (blue curves) using the NRW method.

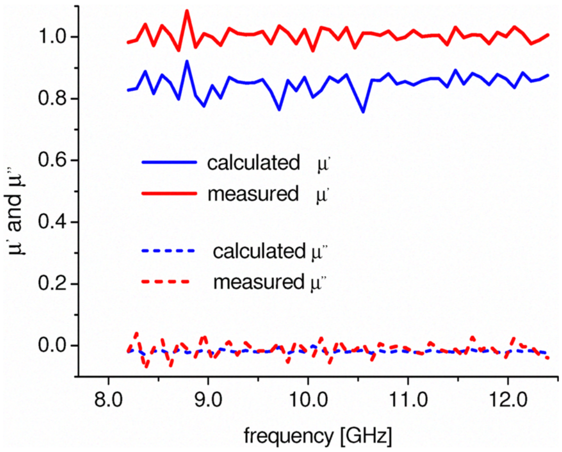

Figure 7. Test sample complex permeability $\mu^* = \mu' = j\mu''$: measured (red curves) and calculated (blue curves) using the NRW method.

II. MATERIALS AND METHODS

To determine the complex permittivity and permeability, we used the two-port transmission/reflection approach, with the material-under-test (MUT), of smooth flat faces and filling the fixture cross section, being placed inside a rectangular waveguide. The sample holder is a precision waveguide section of 140 mm length that is provided with the calibration kit. The electromagnetic parameters were deduced from the scattering matrix defined between the sample planes as shown in Fig. 2. When measuring the scattering parameters, the system is closed with the sample holder placed between adapters 1 and 2 with the adapter of port 1 taken as the reference plane [4-8].

Provided the boundaries of the slab are well defined and the S parameters are accurately known, the following equations allow to relate parameters S_{11} and S_{12} to reflection and transmission coefficients **Γ** and **T**, respectively, to solve the boundary-condition problem at $\ell = 0$ and $\ell = d$ (Fig. 4), such that the reflection coefficient can be expressed as [6,7].

$$\Gamma = K \pm \sqrt{K^2 - 1}, \tag{1}$$

where:

$$K = \frac{\{S_{11}{}^2(\omega) - S_{21}{}^2(\omega)\} + 1}{2S_{11}(\omega)}.$$

The transmission coefficient is given by:

$$\mathrm{T} = \frac{\{S_{11}(\omega) + S_{21}(\omega)\} - \Gamma}{1 - \{S_{11}(\omega) + S_{21}(\omega)\}\Gamma} \tag{2}$$

From (1) and (2), auxiliary variables are defined as follows:

$$x = \frac{\mu_r}{\varepsilon_r} = \left(\frac{1+\Gamma}{1-\Gamma}\right)^2 \tag{3}$$

$$y = \mu_r \cdot \varepsilon_r = \left\{\frac{c}{\omega d}\ln\left(\frac{1}{\mathrm{T}}\right)\right\}^2 \tag{4}$$

$$\mu_r = \sqrt{x \cdot y} \tag{5}$$

$$\varepsilon_r = \sqrt{\frac{y}{x}} \tag{6}$$

For measurements using a rectangular waveguide sample holder, (3) and (4) are rewritten as:

$$\frac{1}{\Lambda^2} = \left(\frac{\varepsilon_r \cdot \mu_r}{\lambda_0^2} - \frac{1}{\lambda_c^2}\right) = -\left[\frac{1}{2\pi d}\ln\left(\frac{1}{\mathrm{T}}\right)\right]^2 \tag{7}$$

$$\mu_r = \frac{1+\Gamma}{\Lambda(1-\Gamma)\left(\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}\right)} \tag{8}$$

$$\varepsilon_r = \frac{\left(\frac{1}{\Lambda^2} - \frac{1}{\lambda_c^2}\right)\lambda_0^2}{\mu_r} \tag{9}$$

where: λ_0 is the free-space wavelength and λ_c the cutoff wavelength of the guide. Since the material is a passive medium the signal of the square root in (1) is determined by the requirement that $\mathrm{Re}(1/\Lambda) > 0$. We note also that (8) and (9) also apply to measurements using a coaxial sample holder, for which $\lambda_c \to \infty$.

III. RESULTS AND DISCUSSION

Measured and calculated scattering parameters are compared in Fig. 5, where it is seen that experimental and numerical S_{21} parameters both coincide at the 0 dB level.

However, we see that the simulated S_{11} curve bends downward for frequencies above 11 GHz, while the measured S_{11} curve shows a slightly negative slope, which indicates interaction of the electromagnetic wave with the material. It is to be noted that in the simulation configuration (Fig. 3), electromagnetic characterization takes place in an ideal environment, where temperature, humidity, misalignment and air gap effects are not taken into consideration.

Then on the basis of the NRW procedure, the simulated S parameters were used to determine ε* and μ*, which are given in Figs. 6 and 7, respectively. We may infer that the bending effect on the simulated S_{11} curve translates into a decrease in ε' at higher frequencies (Fig. 7). Nevertheless, for the remaining parameters the overall agreement between measured and simulated quantities is quite satisfactory.

IV. CONCLUSION

The comparative study of the electromagnetic parameters of a Teflon® slab showed good agreement between measured and simulated complex permittivity and permeability, which were retrieved using the Nicolson-Ross-Weir procedure (NRW), the most commonly used method to perform this calculation. This method has the advantage of being non interactive (no interactive procedure is needed, as required in the Baker-Jarvis method [7]) and applicable to coaxial line and rectangular waveguide cells.

It is well known, however, that the NRW method diverges for low-loss materials at frequencies corresponding to integer multiples of one half wavelength in the sample. At this particular frequency, the magnitude of the measured S11 parameter is particularly small (thickness resonance) and the S11 phase uncertainty becomes large. This leads to the appearance of inaccuracy peaks on the permittivity and permeability curves. But in the present study this method proved to be robust and no anomalies were noticed because resonance for the 5.75-mm-thickness sample would occur above 12.4 GHz.

ACKNOWLEDGMENT

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