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Dielectric Permittivity Estimation of Liquid Phantoms Using a Coaxial Fixture Based on Hybrid PSO-NLR model

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***Abstract*—The estimation of the complex dielectric permittivity of liquid solutions employed in the fabrication of liquid phantoms is pivotal to obtain an accurate dielectric profile and avoid wastes during electromagnetic experiments involving the interaction between EM fields and human body. In this paper, the authors propose a cost-effective and accurate complex dielectric measurement system based on a coaxial fixture and a hybrid Particle Swarm Optimization – Non Linear Regression algorithm. The proposed system is an excellent alternative to existing commercial devices.**

I. Introduction

Human tissue mimicking phantoms have a pivotal role in the validation of electromagnetic experiments and studies that involve the interaction between electromagnetic waves and the human body [1]. Phantoms can come in different states, such as solid, semi-solid or liquid. Liquid phantoms are often preferred because of the ease of manufacture with respect to the other two cases and the possibility of tuning the dielectric properties [2]. The mixing formulae used for the preparation of the phantoms must be followed carefully to obtain an accurate dielectric reproduction of the desired tissue, nonetheless a quick and easy method to estimate the dielectric constant of the mixture should be employed to ensure a good result and avoid wastes. Commercial open-ended coaxial probes are suitable for this task. However, high cost and the re-calibration needed after each measurement hold back this technology. In this paper, we propose an alternative and cost-effective methodology for the estimation of the complex dielectric permittivity of liquid mixtures employed in human phantoms. The proposed system includes a coaxial fixture made of leaded brass, a Vector Network Analyzer (VNA), and a Raspberry Pi 4. The liquid material whose dielectric permittivity needs to be estimated can be placed inside the coaxial fixture. The VNA extracts the S-matrix of the device and this output data are read by the Raspberry Pi 4 that runs an algorithm based on a hybrid Particle Swarm Optimization – Non Linear Regression (PSO-NLR) model, able to provide the complex dielectric profile of the material under test within the frequency range 0.5–3 GHz. In order to validate the proposed methodology, a liquid solution mimicking human muscle tissue in the UHF band (i.e., 867 MHz) has been characterized using the described system and the results have been compared with those obtained with a commercial coaxial probe.

II. Description of the System and Measurement

The coaxial fixture is composed of a total of 7 parts; four of them are independent. A dimensional drawing of the fixture is reported in Fig. 1, for reference. The first and last sections (1 and 7 in Fig. 1) are coaxial cables, in the form of simple commercial coaxial connectors within the final prototype. Sections 4 and 6 are conical sections, wherein the transmission line has been tapered to match the commercial coaxial line with the central section of the device. These sections have a length of 54.4 mm. Sections 3 and 5 have the purpose to separate the central section from the conical ones and effectively shape a space for the sample holder. Their length is equal to 30 mm. Finally, the central section hosts the sample holder which is made out of Poly-lactic Acid (PLA, $\varepsilon_r = 2.54$, $tan\delta = 0.015$) and 3D-printed. As it can be seen from the dimensional drawing, several gaskets, also 3D-printed using PLA filament, are scattered along the coaxial fixture. These spacers have the function of sustaining the entire structure. The whole structure is encapsulated in a leaded brass shell and hold together using long screws and nuts.

The angles ϑ and φ are calculated to maintain the 50 Ω throughout the entire transmission line. The electrical parameters of the material are extracted by a VNA and processed by a Raspberry Pi 4 board that runs a hybrid PSO-NLR algorithm. Through an iterative process, after the conversion of the S-parameters into the transmission matrix, the algorithm is able to estimate the complex dielectric permittivity (i.e., finds the minimum in a given interval solving a least square problem).

To properly test the described system, a liquid solution mimicking the muscle tissue has been prepared, following the recipe found in [3]. The solution comprises de-ionized water (53 wt%), saccharose (45.6 wt%), and sodium chloride (1.4 wt%). This single-tissue mimicking mixture has been first measured using the commercial DAK 3.5 Speag open-ended coaxial probe, providing a reliable comparison for the output of the presented system. A picture of the measurement system is reported in Fig. 2. The results of the complex permittivity estimation of the muscle-like solution with the coaxial fixture and the comparison with the values extracted with the commercial coaxial probe are reported in Fig. 3.

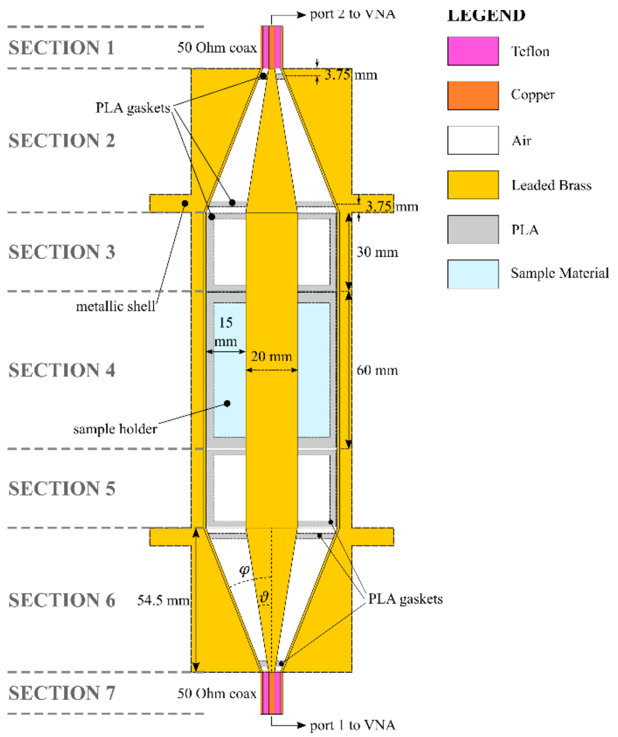

Figure 1. Dimensional drawing of the coaxial fixture, highlighting the sections and the materials.

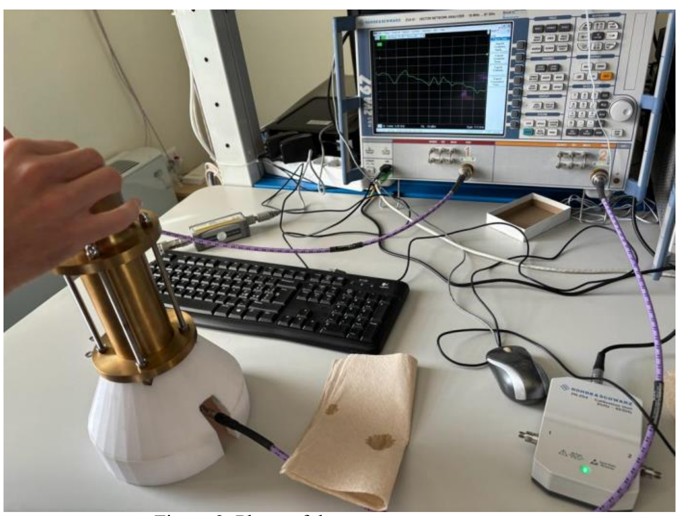

Figure 2. Photo of the measurement system.

From Fig. 3, it can be appreciated the good agreement between the two measurements for both the real (Fig. 3a) and the imaginary (Fig. 3b) part of the complex dielectric permittivity.

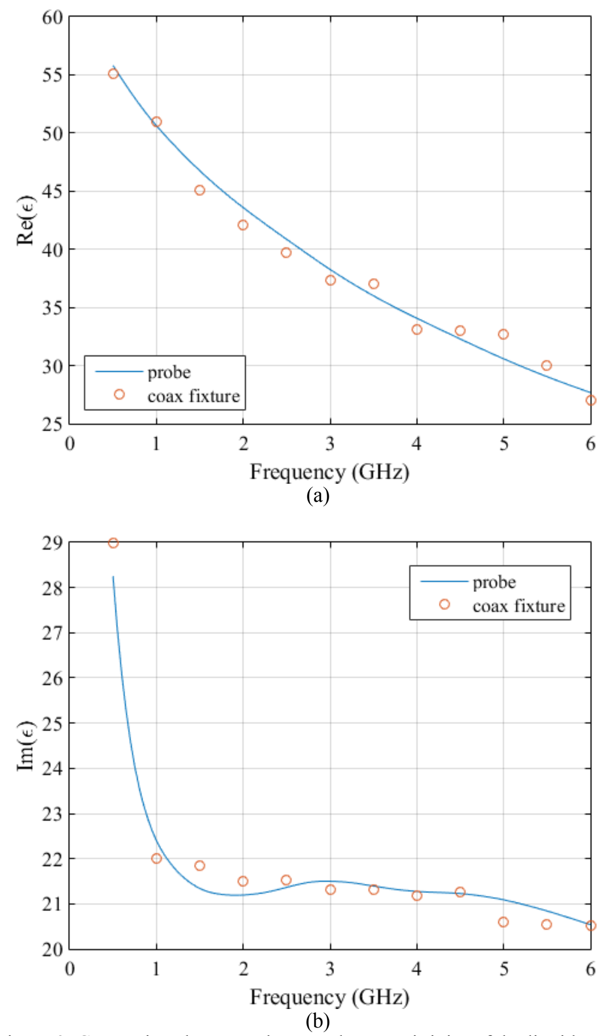

Figure 3. Comparison between the complex permittivity of the liquid muscle phantom measured using the coaxial fixture and a commercial coaxial probe: (a) real part, (b) imaginary part.

These results show that the proposed system is an excellent alternative to existing, more expensive and more complex commercial solution, providing roughly the same level of accuracy. It can be employed to effectively characterize the dielectric profile of liquid mixtures used in the fabrication of human body-mimicking phantoms.

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