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R. Azaro, F. Caramanica, and G. Oliveri

ELEDIA Research Group

Department of Information Engineering and Computer Science

University of Trento, Via Sommarive 14, 38050 Trento - Italy

Tel. +39 0461 882057, Fax +39 0461 882093

E-mail: {*renzo.azaro, federico.caramanica, giacomo.oliveri*}*@disi.unitn.it*

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Abstract

In this paper, an innovative technique for the determination of the dielectric properties of planar substrates is presented. Starting from a set of impedance measurements performed on a section of a microstrip transmission line built on the planar dielectric substrate under test, the proposed technique formulates the reconstruction problem in terms of an optimization one successively solved by means of an effective stochastic algorithm. Such a method allows one the reconstruction of the permittivity values at multiple frequencies by simply using a vector network analyzer and a standard calibration procedure for the impedance measurement. The results of some representative experimental tests are shown for a preliminary assessment of the effectiveness of the proposed approach.

Key words: Permittivity Measurement, Dielectric Substrate Characterization, Microwave Measurements, Particle Swarm Optimizer.

1 Introduction

The knowledge of the dielectric properties of planar substrates is of great importance for an effective design and development of planar antennas [1][2][3] and microwave circuits [4][5][6][7]. This is more important when dealing with low cost materials, whose performances are usually not guaranteed by the producers. Several methodologies have been developed in order to characterize dielectric materials in different frequency bands and with different accuracies. Some techniques are based on the use of resonant systems [10], while other techniques employ non-resonant sections of transmission lines [11][12]. Up to $1\ MHz$, measurements setups are based on lumped-component circuits, while distributed-parameter devices are employed when dealing with higher frequencies. In the latter case, the Material Under Test (MUT) is placed at the terminal section of a coaxial or waveguide transmission line, or inside a resonant cavity. Because of its simplicity and accuracy, the resonant cavity method [10], based on the detection of the resonant frequencies and losses, is widely used when homogeneous materials are considered. On the other hand, the transmission line method [11][12] determines the dielectric properties of the MUT by measuring amplitudes and phases of the signals transmitted and reflected by a material sample inserted in a transmission line. Other techniques devoted to the permittivity estimation in wide frequency bands are still derived from the transmission line method, but they are based on the use of open-ended and non-invasive coaxial probes [13][14]. Moreover, such techniques are generally used to characterize biological tissues [15]. Recently, an interesting method based on the use of a planar four-port microwave device and only-scalar measurements has been proposed in [16], as well.

In order to overcome the need of customized probes or calibration procedures, this letter presents an optimization methodology based on standard impedance measurements. The effectiveness of the proposed approach has been assessed by means of several test cases and two representative examples are presented and discussed in the following.

2 Permittivity Reconstruction Procedure

Let us consider the measurement sample composed by a section of short-ended microstrip transmission line (Fig. 1) and simply obtained by the photolitographic printing of a microstrip line on the planar substrate of MUT. Such a structure is characterized by a length L and a width M, w being the width of the microstrip transmission line. Moreover, t is the height of the conductive strip and h is the height of the planar substrate of the MUT. Besides the geometrical parameters, the electromagnetic behavior of the sample is determined by the conductivity σ of the conductive parts and by the dielectric properties of the substrate [i.e., $\varepsilon_r(f)$ and $tan\delta(f)$ of the MUT]. The two-port circuit is terminated on a short circuit and it is connected to a SMA coaxial connector on the other side, respectively. The input impedance Z_{input} is a function of both the known geometrical parameters and the unknown dielectric properties of the sample under test

$$Z_{input}(f) = Z_{input}\left\{\underline{\alpha},\, \underline{\Lambda}(f)\right\} \tag{1}$$

where $\underline{\alpha} = \{L,\, M,\, w,\, h,\, t,\, \sigma\}$ is the set of known quantities and $\underline{\Lambda} = \{\varepsilon_r(f),\, tan\delta(f)\}$ is the unknown array of the dielectric properties of the MUT to be characterized. The problem of the permittivity characterization is recast as on optimization one. Accordingly, let us define the cost function $\Pi\{\underline{\Lambda}\}$ aimed at quantifying the matching between simulated Z_{input}^{sim} and measured Z_{input}^{meas} input impedance values at the sampling frequencies f_i, $i = 1, ..., I$

$$\Pi\{\underline{\Lambda}\} = \frac{\sum_{i=1}^{I}\left|Z_{input}^{meas}(f_i) - Z_{input}^{sim}(f_i)\right|^2}{\sum_{i=1}^{I}\left|Z_{input}^{meas}(f_i)\right|^2}. \tag{2}$$

In order to minimize (2), an iterative PSO-based procedure is used because of the complexity of the function at hand. The PSO is a robust stochastic search procedure, inspired by the social behavior of insects swarms, proposed by Kennedy and Eberhart in 1995 [17]. Thanks to its features in exploring complex search spaces, PSO has been employed with success in different fields of electomagnetics ranging from from inverse scattering [18][19] and antenna design [20] up to transmission line matching [21]. As regards the problem at hand, the solution is yielded by integrating the PSO-based procedure with a method-of-moments (MoM) [22] electromagnetic simulator devoted to the computation of the input impedance Z_{input}^{sim} in correspondence with a PSO-estimated trial dielectric distribution. The full-wave electromagnetic simultor, developed at ELEDIALab, is able to compute the frequency behavior of the input impedance of the lenght of microstrip transmission line taking into account its geometrical parameters, the frequency-varying dielectric properties of the substrate, the short-circuit boundary condition at the end of the transmission line and assuming as input section the line section at the opposite end. More specifically, the procedure considers a set of trial solutions $\underline{\Lambda}_p^{(k)}$, $p = 1, ..., P$; $k = 0, ..., K$ (p being the trial solution index and k the iteration index). Starting from a randomly-generated (in the worst case when no *a-priori* information are available) initial set $\underline{\Lambda}_p^{(o)}$, a succession of trial solutions is generated according to the PSO strategy [17]. At each iteration k, the optimality of the dielectric reconstruction is evaluated by computing with the MoM simulator the value of the cost function $\Pi_{opt}^{(k)}$ in correspondence with the best trial solution $\underline{\Lambda}_{opt}^{(k)}$ reached up till now (i.e., $\underline{\Lambda}_{opt}^{(k)} = arg\left\{min_{p,k}\left[\Pi\left\{\underline{\Lambda}_p^{(k)}\right\}\right]\right\}$). The iterations stop when a maximum number is reached ($k = K$) or when $\Pi_{opt}^{(k)} \leq \eta$ (η being an user-defined convergence threshold).

3 Numerical Simulation and Experimental Validation

In order to give an indication of the effectiveness of the proposed technique, two representative examples will be described in the remaining of this section.

The first test case is concerned with a sample of planar *FR4* ($\underline{\alpha}^{FR4} = \{L = 80\,mm,\ W = 120\,mm,\ w = 10\,mm,\ h = 1.6\,mm,\ t = 35\,\mu m,\ \sigma = 5.8 \times 10^{-7}\,S/m\}$). Moreover, the other example considers a planar *Arlon* substrate ($\underline{\alpha}^{Arlon} = \{L = 80\,mm,\ W = 60\,mm, w = 10\,mm,\ h = 0.8\,mm,\ t = 35\,\mu m,\ \sigma = 5.8 \times 10^{-7}\,S/m\}$). In order to reduce radiation phenomena from microstrip line and in order to have non negligible attenuation phenomena the samples for measurements and simulations are designed by using low characteristic impedance lines (wider widths of the microstrip) and line lenght longer than a quarter of wavelenght. Figure 2 shows the photos of the two samples of MUT with the short circuits and equipped with the SMA connectors for the input impedance measurements. The short circuit have been made by using a copper sheet having width equal to that of the microstrip transmission line (according to the numerical model used for simulations) and soldered between the trasmission line and the ground plane. In order to measure the input impedance just at the same input section of the microstrip transmission line considered during simulations, before measurements the vector network analyzer (*Anritsu S332D*) has been calibrated with an open circuit, a short circuit and a matched load appositely built using three SMA connectors of the same type of that connected to the samples during impedance measurements. The input data for the reconstruction process have been measured at the frequencies $f_1 = 1.0\,GHz$, $f_2 = 1.5\,GHz$, $f_3 = 2.0\,GHz$, $f_4 = 2.5\,GHz$, and $f_5 = 3\,GHz$ with a vector network analyzer by assuming the transverse plane between the samples and the SMA connectors as reference/calibration section. As far as the PSO is concerned, the following setup has been used: a population of $P = 5$ trial solutions, a threshold equal to $\eta = 10^{-3}$, and a maximum amount of $K = 200$ iterations.

Figure 3 shows the behavior of the cost function versus the iteration number k for both the MUT samples, while the values of the reconstructed permittivity at the frequencies of interest are given in Tabs. I-II, respectively. For completeness, the plots of the impedance values (simulated and measured) are also reported Figs. 4-5 for a comparative assessment. In order to validate the obtained results, the permittivity values obtained with the described methodology have been used to calculate the input impedance of the samples of transmission line under test with an electromagnetic software different from that integrated in the proposed reconstruction technique. To this end a finite-difference time-domain (FDTD) electromagnetic simulator has been employed and the results have been compared with measurements. As expected (also from the value of the cost function at the convergence), there is a good agreement between simulated and measured data in correspondence with both materials and whatever the frequency value. there is a good agreement between the measurements and the data calculated with the reconstructed permittivity values at the same frequency values considered during the recostruction process.

4 Conclusions

In this paper, a method for estimating the dielectric permittivity of planar substrates has been presented. It is based on the use of a PSO-based optimization strategy and it only requires the photolitographic building of one-port MUT samples as well as simple input impedance measurements. For the experimental validation, two different planar substrates of different materials have been considered and the reconstruction results confirmed the reliability and effectiveness of the proposed approach.

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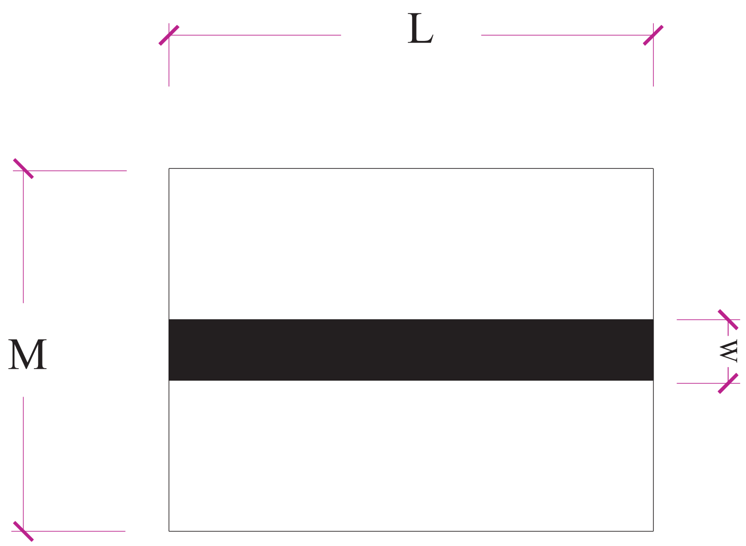
FIGURE CAPTIONS

- **Figure 1.** Geometry of the MUT samples: (*a*) top view; (b) side view.
- **Figure 2.** MUT samples: (*a*) *FR4* and (*b*) *Arlon* substrates.
- **Figure 3.** Iterative cost function minimization. Behaviour of the cost functions vs. the iteration number.
- **Figure 4.** *FR4.* Comparison between simulated and measured impedance values of (*a*) $Re\{Z\}$ and (*b*) $Im\{Z\}$.
- **Figure 5.** *Arlon.* Comparison between simulated and measured impedance values of (*a*) $Re\{Z\}$ and (*b*) $Im\{Z\}$.

TABLE CAPTIONS

- **Table I.** *FR4.* Reconstructed relative permittivity values (real part and loss tangent).
- **Table II.** *Arlon.* Reconstructed relative permittivity values (real part and loss tangent).



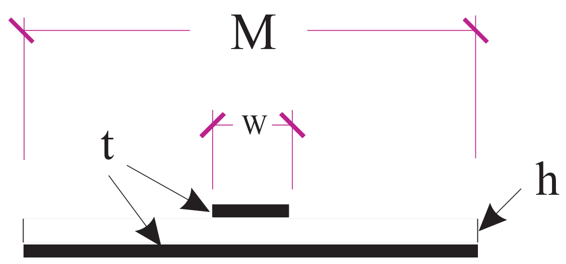
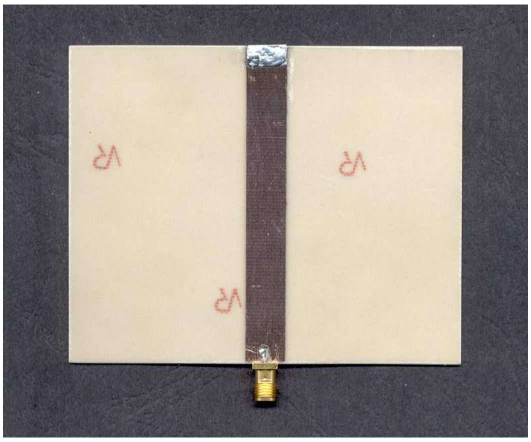
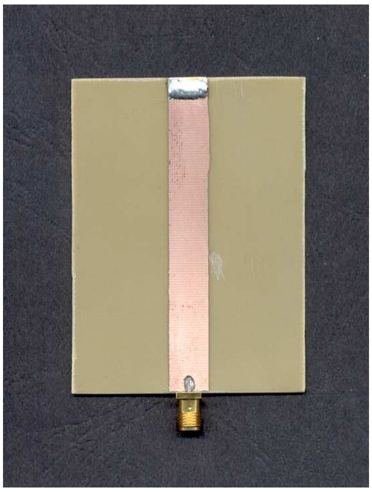


Fig. 1 - R. Azaro *et al.*, "Determination of the complex permittivity ..."



(*a*)



(*b*)

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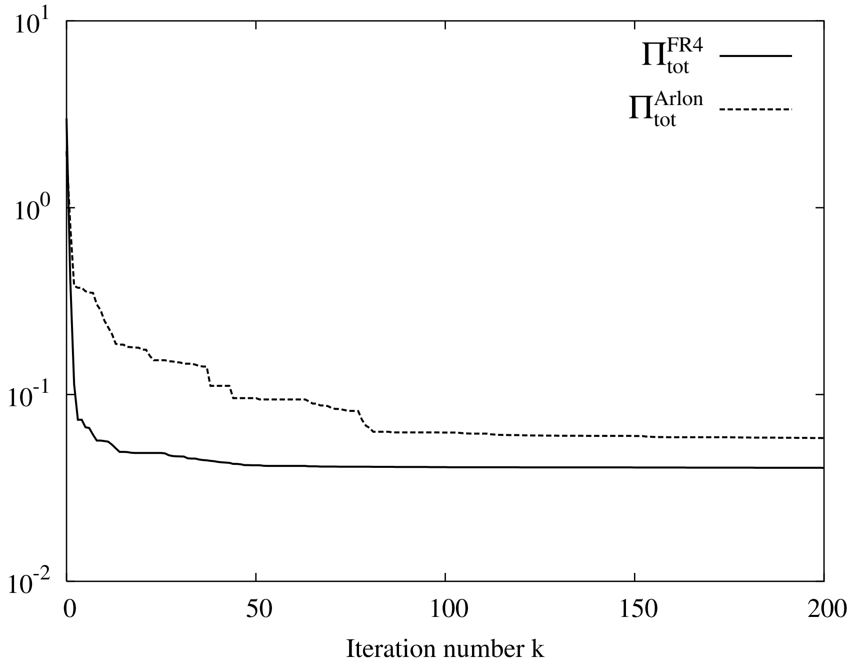

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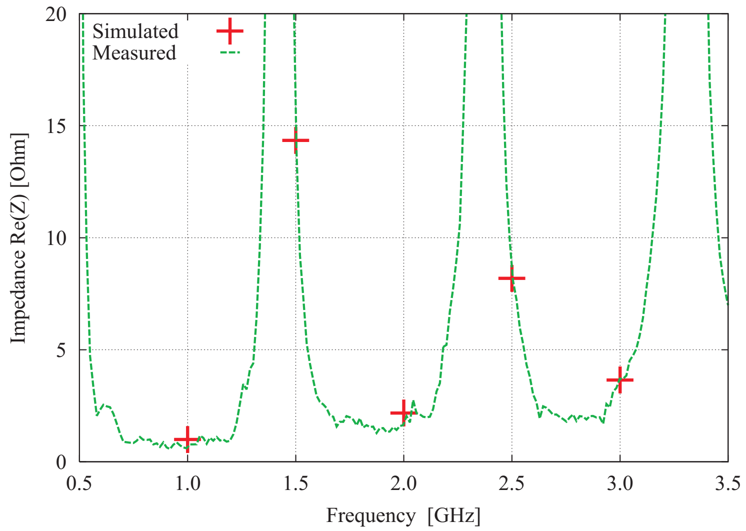
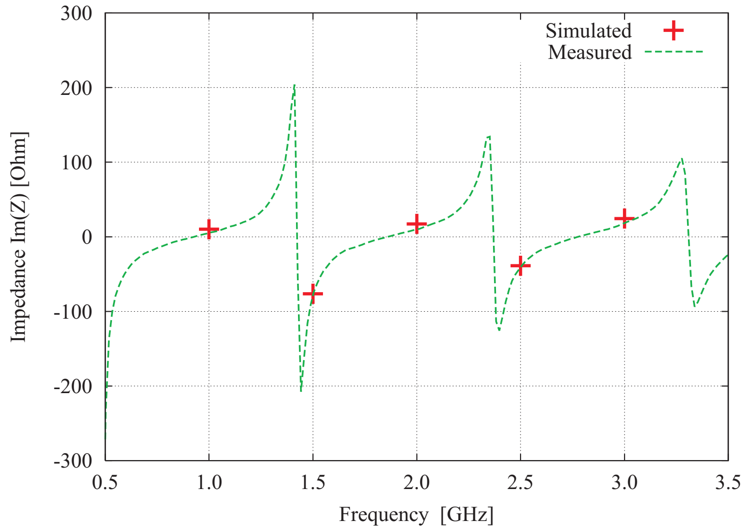


(*a*)



(*b*)

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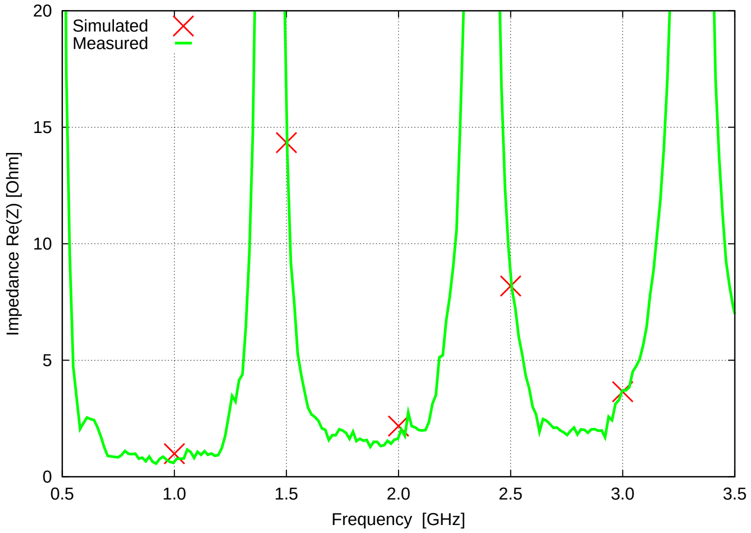

(*a*)

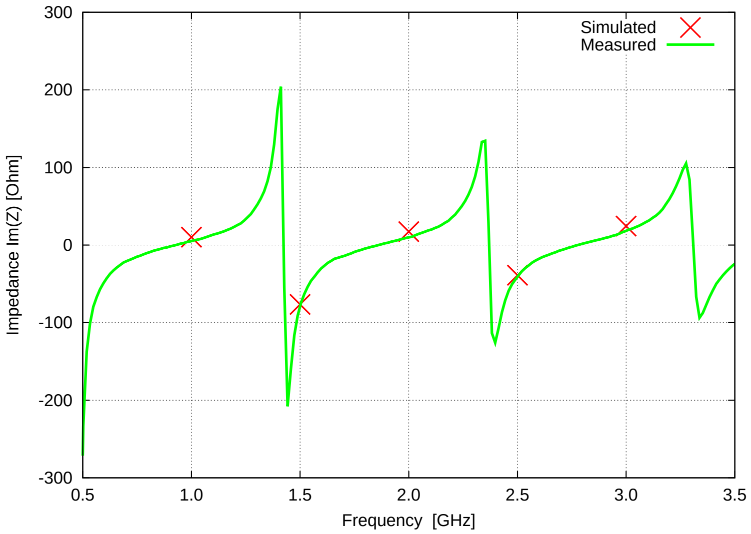

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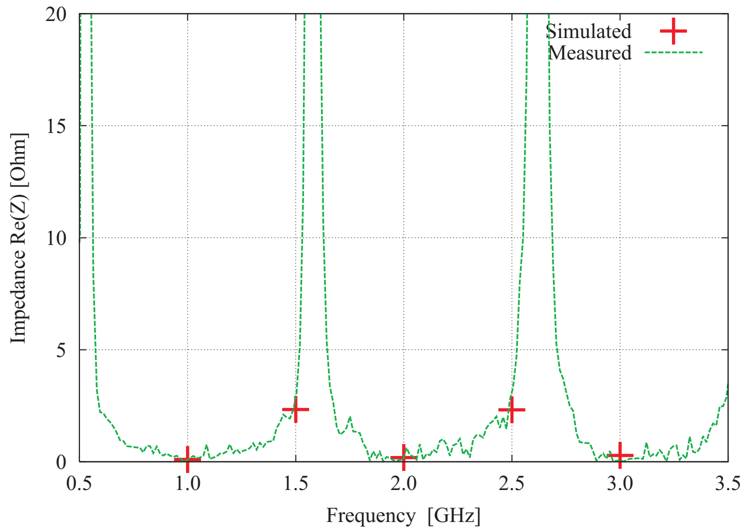
Fig. 4 - R. Azaro *et al.*, "Determination of the complex permittivity ..."



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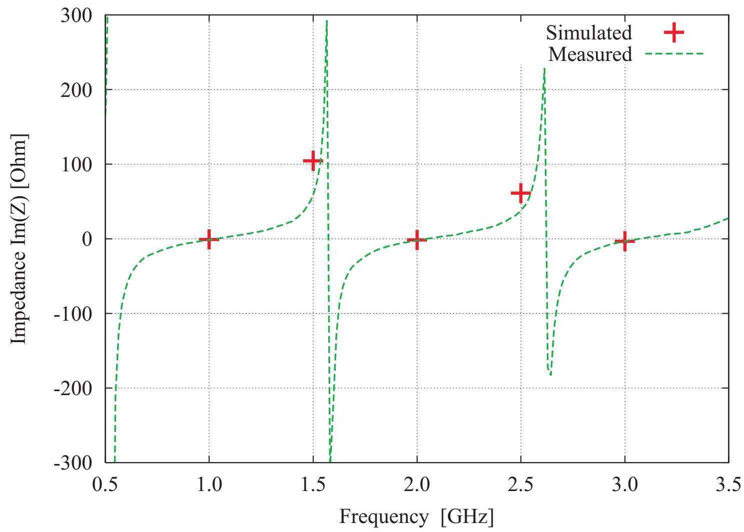

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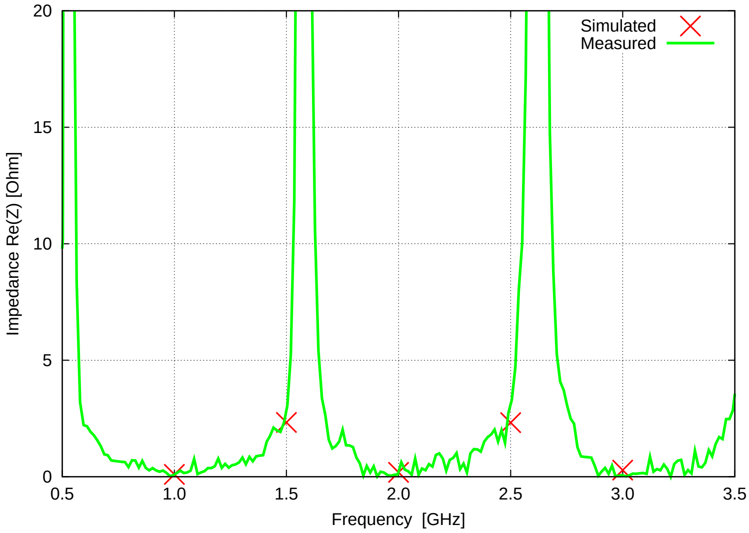
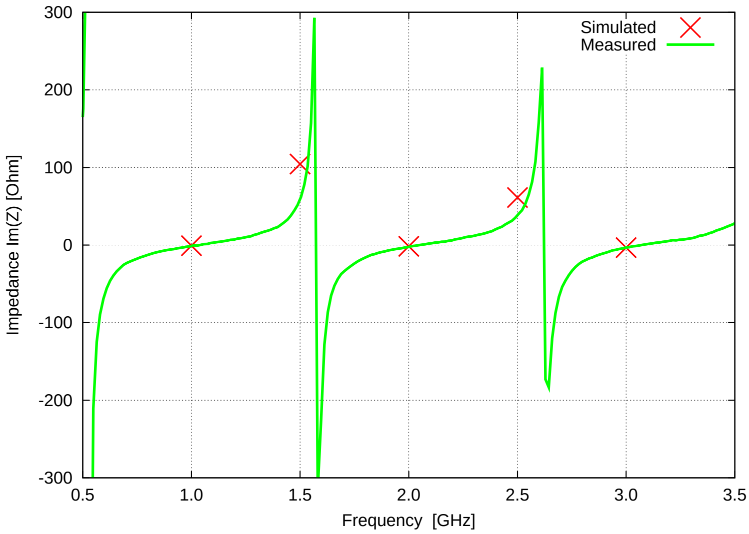
Fig. 5 - R. Azaro *et al.*, "Determination of the complex permittivity ..."



(a)



(b)

Fig. 5 - R. Azaro *et al.*, "Determination of the complex permittivity ..."

Frequency [GHz]	ε_r	$tan\ \delta$
1.0	4.467927	0.024564
1.5	4.120244	0.019092
2.0	4.250521	0.037016
2.5	4.487276	0.016115
3.0	4.248079	0.026322

Tab. I - R. Azaro *et al.*, “Determination of the complex permittivity ...”

Frequency [GHz]	ε_r	$tan\ \delta$
1.0	3.131630	0.002956
1.5	3.131736	0.001443
2.0	3.131643	0.002536
2.5	3.131580	0.002502
3.0	3.149573	0.002147

Tab. II - R. Azaro *et al.*, "Determination of the complex permittivity ..."