

## DETERMINATION OF THE COMPLEX PERMITTIVITY VALUES OF PLANAR DIELECTRIC SUBSTRATES BY MEANS OF A MULTIFREQUENCY PSO-BASED TECHNIQUE

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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.

### 1. INTRODUCTION

The knowledge of the dielectric properties of planar substrates is of great importance for an effective design and development of planar antennas [1–3] and microwave circuits [4–7]. 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,

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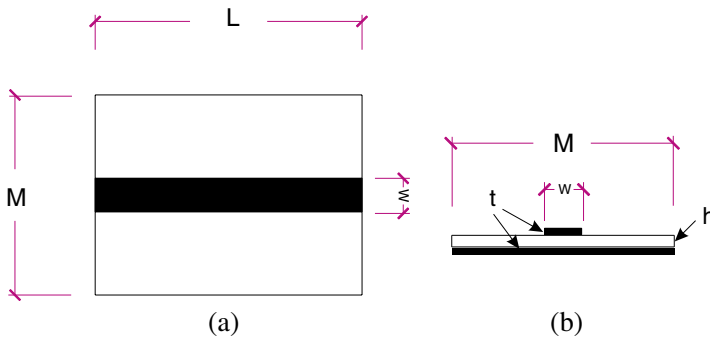
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while distributed-parameter devices are employed when dealing with higher frequencies. In the latter case, the Material Under Test (MUT) is placed at the terminal section of a coaxial or waveguide transmission line, or inside a resonant cavity. Because 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 photolithographic printing of a microstrip line on the planar



**Figure 1.** Geometry of the MUT samples: (a) Top view; (b) side view.

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  $\sigma$  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

$$Z_{input}(f) = Z_{input}\{\underline{\alpha}, \underline{\Lambda}(f)\} \quad (1)$$

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 an 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  $f_i$ ,  $i = 1, \dots, I$

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

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 electromagnetics ranging 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 simulator, developed at ELEDIALab, is able to compute the frequency behavior of the input impedance of the length 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  $\underline{\Lambda}_p^{(k)}$ ,  $p = 1, \dots, P$ ;  $k = 0, \dots, K$  ( $p$  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  $\underline{\Lambda}_p^{(0)}$ , 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  $\Pi_{opt}^{(k)} \leq \eta$  ( $\eta$  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* ( $\underline{\alpha}^{FR4} = \{L = 80 \text{ mm}, W = 120 \text{ mm}, w = 10 \text{ mm}, h = 1.6 \text{ mm}, t = 35 \text{ }\mu\text{m}, \sigma = 5.8 \times 10^{-7} \text{ S/m}\}$ ). Moreover, the other example considers a planar *Arlon* substrate ( $\underline{\alpha}^{Arlon} = \{L = 80 \text{ mm}, W = 60 \text{ mm}, w = 10 \text{ mm}, h = 0.8 \text{ mm}, t = 35 \text{ }\mu\text{m}, \sigma = 5.8 \times 10^{-7} \text{ S/m}\}$ ). 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 length longer than a quarter of wavelength. Fig. 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 Tables 1, 2, respectively. For completeness, the plots of the impedance

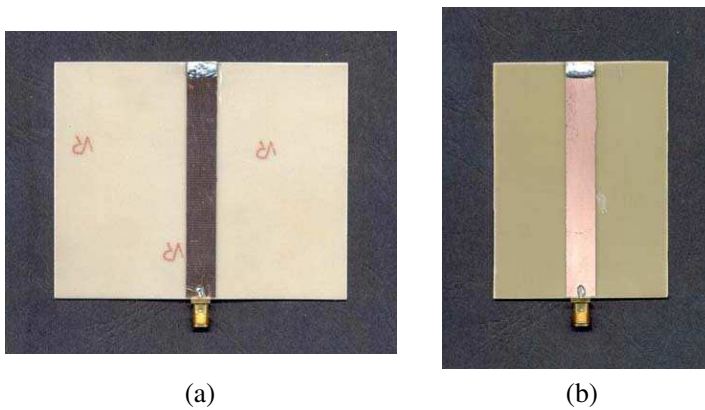


Figure 2. MUT samples: (a) FR4 and (b) Arlon substrates.

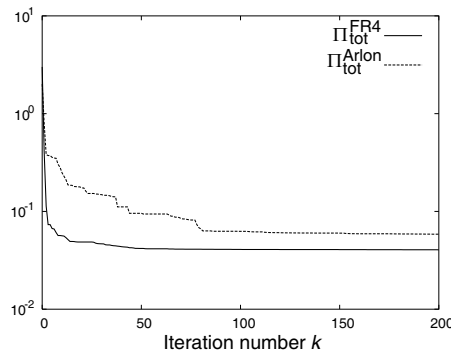


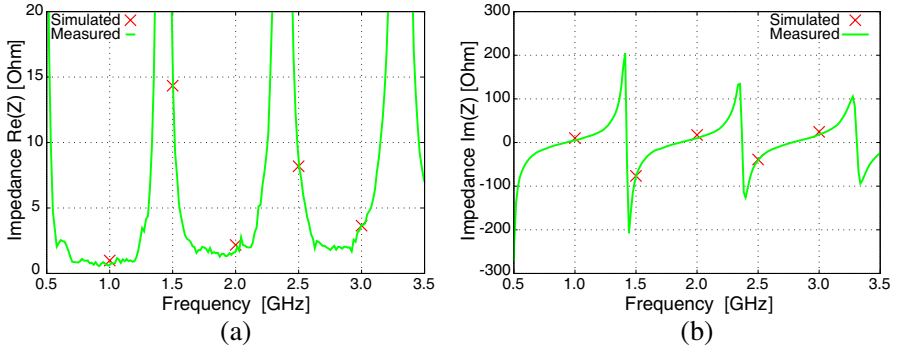
Figure 3. Behaviour of the cost functions vs. the iteration number.

**Table 1.** *FR4*. Reconstructed relative permittivity values (real part and loss tangent).

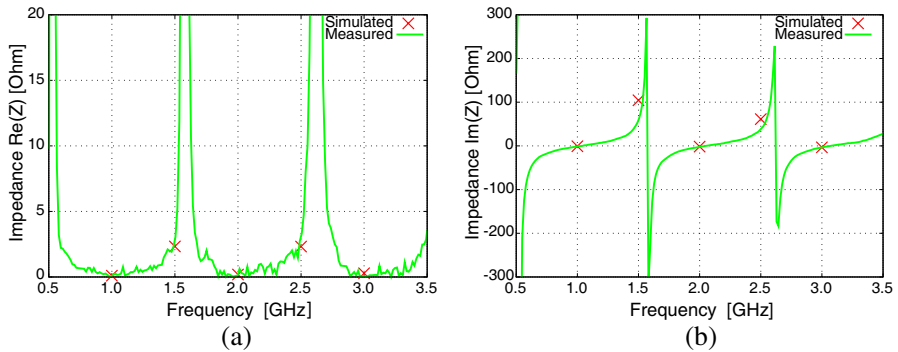
Frequency [GHz]	$\varepsilon_r$	$\tan \delta$
1.0	4.467927	0.024564
1.5	4.120244	0.019092
2.0	4.250521	0.037016
2.5	4.487276	0.016115
3.0	4.248079	0.026322

**Table 2.** *Arlon*. Reconstructed relative permittivity values (real part and loss tangent).

Frequency [GHz]	$\varepsilon_r$	$\tan \delta$
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

**Figure 4.** *FR4*. Comparison between simulated and measured impedance values of (a)  $\text{Re}\{Z\}$  and (b)  $\text{Im}\{Z\}$ .

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



**Figure 5.** *Arlon*. Comparison between simulated and measured impedance values of (a)  $\text{Re}\{Z\}$  and (b)  $\text{Im}\{Z\}$ .

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 the measurements and the data calculated with the reconstructed permittivity values at the same frequency values considered during the reconstruction 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 photolithographic 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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