Dissipation Factor and Permittivity Estimation of Dielectric Substrates Using a Single Microstrip Line Measurement

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Abstract ─ The knowledge of the dielectric properties of materials, for the design of several components and circuits at high frequencies, is mandatory. In this paper, we present a simple method for the estimation of the dissipation factor (loss tangent) of dielectric materials based on the reflection measurement of a single microstrip line, which is applied to some common known materials, such as FR-4 and Rogers RO3010 laminates. The obtained results match well with the data on the literature for the considered materials.

Index Terms ─ Dielectric characterization, loss factor estimation, microwaves, permittivity estimation.

I. INTRODUCTION

Adaptability and integration of electronic systems is a major concern for current design engineers. In order to promote these, even at high frequencies, new solutions are constantly being proposed. One of those, is the use of alternative substrate materials [1,2].

Common substrates, used for the design of antennas and circuits for RF applications, can be replaced by other materials, that are, most of the times, easily available and preferably less expensive and ecofriendly; like plastic, fabrics, paper, or ceramics.

A very clear example is RFID (radio frequency identification) which is responsible for an increased diversity of the electronics printing techniques. It's being extensively used in many different kinds of applications and is one of the most promising bets for the development of the Internet of Things concept [3]. RFID systems operating in the HF (high frequency) band have been designed upon paper and plastic surfaces for mass production and implementation at the lowest costs possible. However, this has been done due to the low frequency of operation and simplicity of the system design. When the application envisioned is operating at UHF (ultra high frequency) or microwave frequencies there are more limitations and constraints to consider when designing the system.

According to [4], printed antennas and transmission lines have dimensions directly related to the wavelength, and hence the frequency of the desired system. The wavelength is dependent on the permittivity and permeability of the propagation medium. Therefore, in order to efficiently design a printed antenna or RF circuit, the electrical properties: relative permittivity (ε_r); relative permeability (μ_r); and the dissipation factor, also known as loss tangent (tan δ), of the substrate must be known.

The information regarding these parameters is commonly found on the laminate's datasheets, but this does not happen for common materials not intended for electronic applications (e.g., fabrics, ceramics, paper, or plastic). So when designing RF circuitry using such materials, characterization in terms of permittivity and losses must be performed. In many cases, the substrates are dielectric non-magnetic materials; therefore, the relative permeability is unitary.

Permittivity and loss estimation is an old research subject and there's extensive literature regarding several methods to characterize different kinds of materials that can be found in reviews [5], application notes [6] and books [7]. In many of these methods, specific equipment is required, and might not be available in every lab.

The simplest methods available that allow the estimation of the permittivity, require the measurement of the scattering parameters of microstrip lines, such as presented in [8,9]. In these proposals, the dielectric under test is used as the substrate for the microstrip lines. Two different lines, with different lengths are required, for which the exact lengths and widths must be known with high precision. Other possibility is presented in [10], using a similar approach based on two lines with different lengths, but in which the material under test is placed above the lines, as a superstrate.

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In this paper, we propose a method that only requires a single measurement of the reflection coefficient of an open-ended microstrip line, for the estimation of the permittivity and dissipation factor of the line substrate. The dissipation factor estimation proposed is the actual novelty. It is shown, that the proposed method can achieve better estimations when compared to other common methods, and does not require any prior knowledge of the conductivity, or other sources of losses, in the line. Since the permittivity is required for the calculation of the dissipation factor, we show the steps based on transmission line theory and microstrip line theory that allow the estimation of its value.

This paper is organized as follows. In the following section we present the steps for the permittivity and loss estimation based on reflection of microstrip lines method. In Section III we explain the experimental setup and present the results for permittivity and loss tangent obtained through measurements of different dielectric samples; namely, FR-4, Plastic and a Rogers RT5880. Finally, Section IV contains the uncertainty analysis of the proposed method, and Section V presents the conclusions.*Z*

II. PERMITTIVITY AND DISSIPATION FACTOR ESTIMATION: THEORY

Microstrip lines are simpler to design and fabricate when compared to coplanar or striplines. Especially if we consider creating such lines in a material that doesn't have electrodeposited conductors and where such processes are very hard and costly to apply.

As mentioned in the previous section, there are other approaches to characterize dielectric materials that can be made with microstrip lines. However, it requires the development of two lines, with different lengths, in which, the lengths, width and the height of the substrate must be known with high precision. Any error present in this dimensions can lead to large errors in the permittivity estimation. Especially an error in the width of the lines or in the length difference between them. By using a single microstrip line we avoid this sources of errors.

In order to determine the dissipation factor of a given material, its permittivity value is needed. Therefore, if not accessible in references, one must first assess its value. In the following subsection we describe a way to calculate it based on the measurement of a single microstrip line. It is derived from the known transmission line and microstrip line theory. In Subsection B, we present the techniques to determine the dissipation factor along with our novel approach.

A. Permittivity estimation with a microstrip line

If we terminate a transmission line with an open-circuit ($Z_L=\infty$) then, according to [4], the impedance seen at the entrance of the line along l is:

$$Z_{in} = \frac{Z_0}{\tanh\left(\alpha l + j\beta l\right)}, \tag{1}$$

being Z_0 the characteristic impedance of the line and α and β the propagation attenuation and phase constant. Considering $\beta = 2\pi/\lambda$ and $l = \lambda_r/2$, where λ_r is the wavelength at the line resonance, then we have $\beta l = \pi f/f_r$. If we replace this into (1), separate the real from the imaginary part, and consider the input impedance at one fourth of the resonant frequency ($\beta l = \pi/4$), then (1) becomes:

$$Z_{in} = Z_0 \left\{ \frac{2\tanh(\alpha l)}{1+\tanh^2(\alpha l)} - j\frac{1-\tanh^2(\alpha l)}{1+\tanh^2(\alpha l)} \right\}. \tag{2}$$

If we assume the losses are positive (which is correct for the majority of materials), and considering $Z_{in} = R - jX$, we can say:

$$\tanh(\alpha l) = -\frac{X}{R} + \sqrt{\left(\frac{X}{R}\right)^2 + 1}, \tag{3a}$$

$$Z_0 = X\frac{1+\tanh^2(\alpha l)}{1-\tanh^2(\alpha l)} = R\frac{1+\tanh^2(\alpha l)}{2\tanh(\alpha l)}. \tag{3b}$$

This process to determine the characteristic impedance of the line is rather simple, since we just have to measure the input impedance of the line at one fourth of the first resonant frequency, which can be done simply with a network analyzer. With that impedance value we can calculate (3a) and then determine the characteristic impedance with (3b).

With the knowledge of the characteristic impedance of the line we can relate it to the effective permittivity of the substrate. For a microstrip line, according to [11], we have:

$$\varepsilon_{eff} = \left(\frac{60}{Z_0}\ln\left(\frac{8h}{W} + \frac{W}{4h}\right)\right)^2, \tag{4a}$$

$$\varepsilon_{eff} = \left(\frac{120\pi}{Z_0}\frac{1}{\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)}\right)^2, \tag{4b}$$

where (4a) should be used when $W/h \le 1$, and (4b) when otherwise. Being W the width of the microstrip line and h the height of the substrate. These can be solved for the relative permittivity of the substrate as:

$$\varepsilon_r = \frac{2\varepsilon_{eff} + \frac{1}{\sqrt{1+12\,h/W}} - 1}{1 + \frac{1}{\sqrt{1+12\,h/W}}}. \tag{5}$$

B. Dissipation factor estimation with a microstrip line

The dissipation factor, also known as loss tangent ($\tan\,\delta$), of a dielectric material in a microstrip line substrate, can be related, according to [4], to the attenuation of the dielectric material (α_d) as:

$$\tan\delta = \frac{\alpha_d \sqrt{\varepsilon_{eff}}\,(\varepsilon_r - 1)}{\pi\varepsilon_r\,(\varepsilon_{eff} - 1)}\frac{c}{f}. \tag{6}$$

The total attenuation applied to the propagation is characterized by the sum of the dielectric, conductor, radiation and leakage losses. In order to determine the losses from the dielectric the total loss and the contribution from each of the other sources must be known. The total attenuation can be determined from the input impedance measurement as shown in (3a) or by:

$$\alpha = -\frac{\ln(|T|)}{l}, \tag{7}$$

where T is the transmission parameter which is determined according to the NRW (Nicolson-Ross-Wier) method [12,13]. The conductor losses can be calculated using empiric closed form expressions as shown in [14]. However, these expressions are empirical, meaning they're dissociated from what actually is being measured and are frequency independent. Since the losses from the dielectric change with frequency, a small error in the calculation of the conductor losses can lead to a large error in the overall result. Besides, it is very hard to account the contribution from radiation and leakage losses. Even though leakage can be negligible and radiation is more significant for high microwave and/or millimeter wave frequencies. Therefore, we developed an iterative method to calculate the dissipation factors that does not require knowledge of the radiation, conductor or leakage losses and still provides reasonable estimations.

Considering a lossless line, with perfect conductors and a lossless substrate, terminated in an open circuit, then the input impedance measured at the resonant frequency of the line is infinite. However, when considering the losses, either from the conductor or dielectric, the input impedance decreases as the losses rise.

Using ADS Momentum EM simulator, we designed several lines with different lengths and widths and changed the characteristics of the substrate material. Some of the simulated lines and the corresponding impedance values obtained are presented in Table 1. Where z_{in} is the normalized input impedance, at the resonant frequency, when considering perfect conductors (the only source of considerable loss is from the dielectric). While z_c is the normalized input impedance, considering also the conductor losses.

It is noticeable from the presented values, that there is a decrease in the input impedance as the losses increase. Besides, there is a direct proportionality between the characteristic impedance of the lines and the input impedance at resonance. We can see this tendency in Fig. 1, where the variation of the characteristic impedance of several lines with their input impedance at resonance, considering tan δ = 0.01, is depicted. Moreover, it is also shown a possible linearization of this relation, as:

$$z_{in} = 1.95Z_0 - 27.4, \tag{8}$$

and since the loss tangent is inversely proportional to this input impedance, we reach:

$$\tan\delta = \frac{0.0195Z_0 - 0.274}{z_{in}}. \tag{9}$$

This expressions can give a first estimation of the loss tangent. However, it only takes into account the dielectric loss. In order to consider the remaining sources of losses in the microstrip line, for the correct calculation of the dissipation factor, we consider a normalized impedance z_m that tends towards z_{in} as the conductivity increases, which can be also devised by the results on Table 1. We approximate this relationship according to expression (10):

$$z_m = z_{in}\left(1 - Ke^{\frac{Z_0 W}{\tau}}\right)^{-1}. \tag{10}$$

So by knowing the characteristic impedance of the line, the width of the line and the factors K and τ, one can determine an equivalent input impedance z_m and then determine a more accurate estimation of the loss tangent with (9) by replacing z_{in} with z_m. To reach the correct factors K and τ, we can rearrange (10) in order to get a relation between K, τ and Z_0W, being W expressed in millimeters, as:

$$Z_0 W = -\tau \ln\left(1 - \frac{z_m}{z_{in}}\right) + \tau \ln K, \tag{11}$$

since z_m is the input impedance considering all the losses, which will tend towards z_{in} as the conductivity increases, one can calculate the K and τ factors for different loss tangents and different conductivity values. By doing so, we reached the values presented in Table 2.

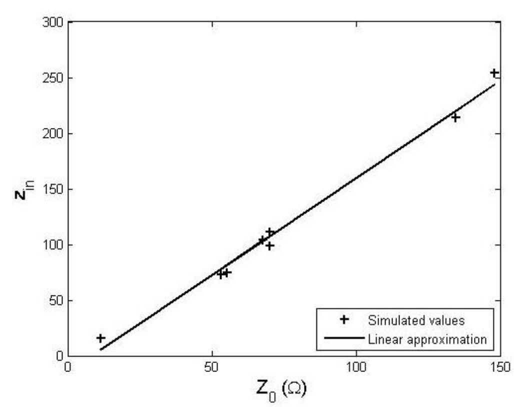

Fig. 1. Relation between the characteristic impedance of microstrip lines and the input impedance at resonance for perfect conductor lines.

Table 1: Input impedance of microstrip line simulations using ADS Momentum for different substrate materials

Line Properties	tan δ	z_{in} (Ω)	σ (S/m)	z_c (Ω)
Line 1 Z0 = 11.53 W = 2 mm h = 0.1 mm ε_r = 2	0.01	15.55	1.0E6	3.03
			10.0E6	5.87
			60.0E6	9.01
	0.03	5.15	1.0E6	2.20
			10.0E6	3.35
			60.0E6	4.17
	0.05	3.07	1.0E6	1.73
			10.0E6	2.34
			60.0E6	2.70
Line 2 Z0 = 53.23 W = 1 mm h = 1 mm ε_r = 8	0.01	72.77	1.0E6	30.43
			10.0E6	46.99
			60.0E6	58.28
	0.03	24.20	1.0E6	16.62
			10.0E6	20.51
			60.0E6	22.42
	0.05	14.49	1.0E6	11.42
			10.0E6	13.10
			60.0E6	13.84
Line 3 Z0 = 70.18 W = 2 mm h = 1 mm ε_r = 1.8	0.01	110.94	1.0E6	60.39
			10.0E6	47.28
			60.0E6	48.91
	0.03	36.77	1.0E6	28.50
			10.0E6	33.09
			60.0E6	35.08
	0.05	21.93	1.0E6	18.94
			10.0E6	20.67
			60.0E6	21.38
Line 4 Z0 = 148.13 W = 1 mm h = 3 mm ε_r = 2	0.01	254.03	1.0E6	137.74
			10.0E6	190.75
			60.0E6	221.63
	0.03	84.09	1.0E6	65.18
			10.0E6	75.63
			60.0E6	80.19
	0.05	50.29	1.0E6	43.29
			10.0E6	47.28
			60.0E6	48.91

Table 2: Calculated K and τ factors for different simulated microstrip lines

tan δ	σ (MS/m)	τ	K
0.01	1.0	210.63	0.858
	10.0	141.62	0.673
	60.0	118.54	0.426
0.03	1.0	139.59	0.600
	10.0	114.82	0.349
	60.0	105.18	0.185
0.05	1.0	125.45	0.436
	10.0	109.28	0.228
	60.0	103.62	0.114

According to these values, we can see that there is an inverse linear relation of K and τ with the square root of the conductivity as depicted in Figs. 2 and 3.

Based on these results, we can write K and τ in the form:

$$K = \frac{a_K}{\sqrt{\sigma_a}} + b_K, \tag{11a}$$

$$\tau = \frac{a_\tau}{\sqrt{\sigma_a}} + b_\tau, \tag{11b}$$

where σ_a is an educated guess of the conductivity value and the factors a_τ, a_K, b_τ and b_K, are obtained from a linearization that relates to the loss tangent as follows:

$$a_K = -2.105 \tan\delta + 0.475, \tag{12a}$$

$$b_K = \frac{0.0644}{\sqrt{\tan\delta}} - 0.203, \tag{12b}$$

$$a_\tau = -1991.0 \tan\delta + 115.6, \tag{12c}$$

$$b_\tau = \frac{1.097}{\sqrt{\tan\delta}} + 95.53, \tag{12d}$$

Since these factors depend on the loss tangent itself, we need an iterative method in order to solve this problem.

The algorithm is described as follows: We start by calculating a first approximation to the loss tangent with (9), after that we can calculate the K and τ factors that allow the calculation of (10). Using that new estimated impedance we can recalculate the loss tangent with (9), by replacing z_{in} with z_m.

A good approximation for the loss factor is achieved usually after four iterations. The convergence graphic is shown in Fig. 4.

A comparison about the estimation of the loss tangent with three different methods is shown in Fig. 5. These results are obtained from simulation for dielectrics with different losses (0.01, 0.02 and 0.005).

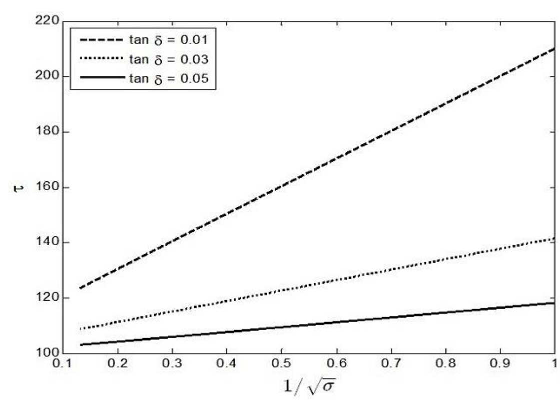

Fig. 2. Relation between the τ coefficient and the conductivity of the line conductors for different loss tangent values.

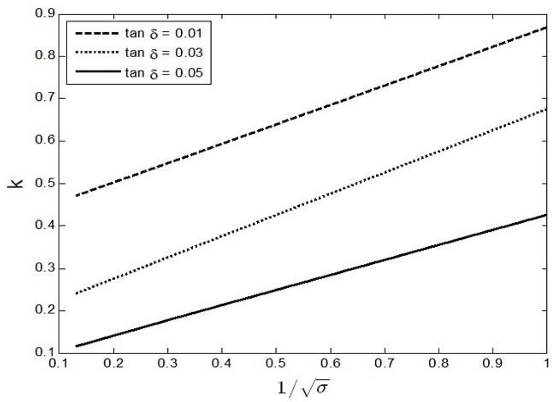

Fig. 3. Relation between the K coefficient and the conductivity of the line conductors for different loss tangent values.

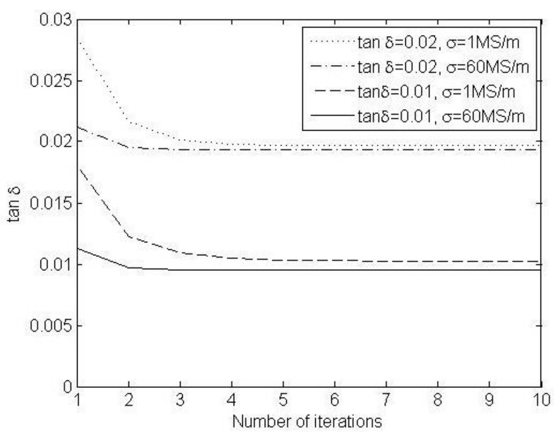

Fig. 4. Convergence of the dissipation factor determination method with the number of iterations, for different conductivities and dielectrics losses.

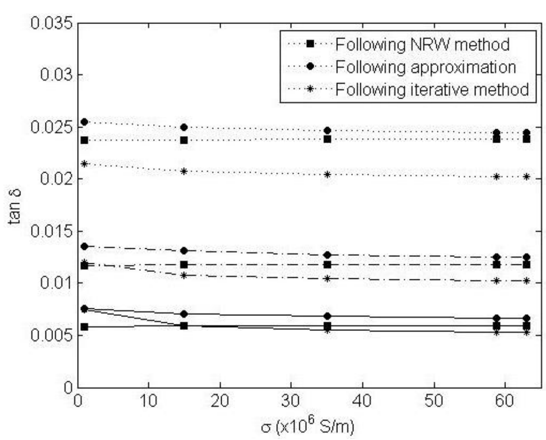

Fig. 5. Loss tangent determination for different loss dielectrics with NRW method, approximation (3a) and the iterative method.

From the results in Fig. 4 we can see that, independently of the loss tangent or the conductivity losses, the method converges for a very reasonable value after the fourth iteration. Moreover, even for very different conductor loss values, the method converges for a very approximate dielectric loss; therefore, showcasing low dependence on this parameter. This means that even if the conductivity value is not precise, one can reach accurate dielectric loss values.

It is clear, from the results depicted in Fig. 5, that the iterative method proposed leads to better estimations of the loss tangent, independently of the dielectric or conductor losses, when compared to other estimation methods.

III. PERMITTIVITY AND DISSIPATION FACTOR ESTIMATION: MEASUREMENTS

To ensure the accuracy of the results obtained by applying the previously described expressions, we tried to characterize three different dielectric substrates, from low to higher permittivity and different losses. The three dielectrics used are presented in Fig. 6.

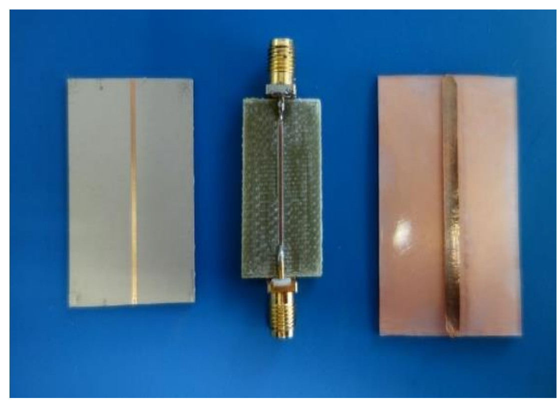

Fig. 6. Picture of the transmission lines tested. From left to right: Rogers RT6010 substrate, FR-4 substrate and LDPE (low density polyethylene) substrate.

There is no special considerations to take for the microstrip line dimensions. However, one thing to keep in mind which might help to achieve better results, is to have a ratio of the width of the line (W) to the height of the substrate (h) such that avoids being in the border intervals as referenced for the calculations of (4).

As we can see from Table 3, we used different ratios for the line, so that the calculations would fall into the different intervals for each.

The microstrip lines on the Rogers and the FR-4 substrates were etched traditionally, using a milling process. For the plastic, since these had no conductor electrodeposited in it, we used copper tape for the conductive parts of the lines.

Table 3: Dielectric substrate samples physical dimensions

Material	L (cm)	H (mm)	W (mm)	Ws (mm)
FR-4	3.96	1.59	0.8	18
Rogers RT6010	4.42	0.635	1.0	26
LDPE	4.60	1.00	1.16	31

The first step to extract the permittivity is therefore to measure the input impedance of the line with an open circuit in the end. Ensuring that the line is ended in an open circuit is important, connecting an open circuit load from the VNA calibration kit is a way to ensure it. Leaving an open terminated line or an SMA connector does not guarantee an open circuit for the frequency band in consideration, which leads to errors in the loss determination.

To calculate the permittivity of the considered lines first we need to measure the characteristic impedance of the line, which is the real part of the measured the input impedance at one fourth of the resonant frequency. With the input impedance value we can use expression (3) in order to calculate the characteristic impedance of the line. With the characteristic impedance of the lines we use expression (4) to extract ε_{eff}. In order to obtain better results we can consider the effective width of the lines (W_e), as described in [11]. With the effective permittivity we can then calculate the relative permittivity of the substrate with (5).

As for the loss tangent determination the iterative method as described in the previous section should be used. The method stops when the variation of the value between iterations is very small or when you reach a negative value, in which case, the current and previous values should be discarded and second to last value obtained is the one considered the closest to the loss tangent of the dielectric under test.

The results obtained for the considered lines based on the measurements and calculations described, yield the results presented in Table 4.

Table 4: Estimated values of the three sample dielectric slabs based on the proposed method and reference values from literature

Sample	Z_0 (Ω)	ε_r	Ref. ε_r	tan δ	Ref. tan δ
FR-4	93.3	4.29	4.30 – 4.70	0.018	0.025
Rogers RT6010	36.9	10.15	10.20	0.003	0.0023
LDPE	84.8	2.30	2.20 – 2.35	0.07	0.001

Comparing the obtained values for the permittivity and the dissipation factor with the reported values in the materials datasheets we can see a good agreement. However, these values are only relative references since the frequencies and methods used to characterize such materials differ. Besides, it is known, as stated earlier, that these parameters are dependent on frequency and temperature. Therefore, it is expected to observe some differences regarding the estimated values.

IV. UNCERTAINTY ANALYSIS

Although the results reported in the previous section match closely with reported values in the materials datasheets, the reliability of the characterization method must be assessed. In order to do so, we did a set of measurements to the same microstrip lines and verified the error and variation obtained for the permittivity and the loss tangent.

Every measurement is susceptible to errors and therefore it is important to assess the sources of possible mismatches than can occur during measurement that lead to errors in the results. The method proposed here has a few sources which can introduce errors. Those are the measurement of the physical dimensions of the microstrip line, the error occurring from the uncertainty of the VNA, the use of SMA connectors or a test fixture for transmission lines and the added losses from corrosion of the material.

The contribution of some of these sources of error are nearly impossible to separate from the others; therefore, in this section we show the results obtained from several measurements performed to the microstrip lines and analyze the variations of each main parameter that occur in order to certify the robustness of the method.

It is depicted in Figs. 7 and 8 the probability functions, obtained from the measurements of the three dielectric samples, for the permittivity and loss tangents.

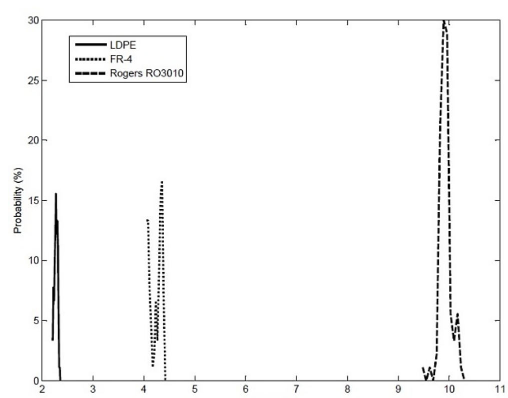

Fig. 7. Probability function of the microstrip lines substrate permittivity (ε_r).

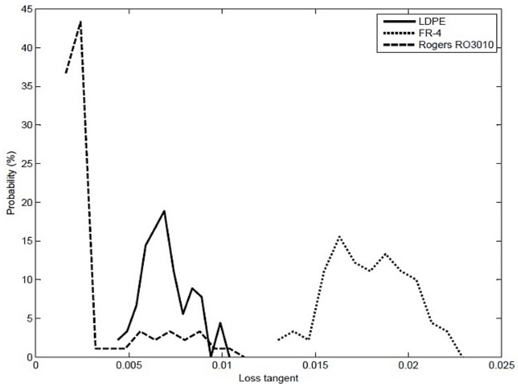

Fig. 8. Probability function of the microstrip lines substrate loss tangent (tan δ).

The uncertainty is characterized by the standard deviation observed in a probability function obtained from a large set of measurements performed under the same conditions. Table 5 resumes the mean values and uncertainty values obtained for the different parameters for each of the dielectric slabs.

Table 5: Mean values and uncertainty obtained in the measurement of the different dielectric sample materials

Sample		f_0 (MHz)	Z_0 (Ω)	ε_r	tan δ
FR-4	$\overline{X}$	1453	93.32	4.32	0.019
	$\overline{U}$	6.91	1.13	0.12	0.002
Rogers RT3010	$\overline{X}$	1152	36.89	10.16	0.003
	$\overline{U}$	65.4	0.48	0.28	0.002
LDPE	$\overline{X}$	1344	84.80	2.30	0.007
	$\overline{U}$	1.82	0.40	0.027	0.0012

From the results obtained we can see that the estimation of the permittivity of the LDPE and FR4 are rather accurate, with obtained values in close relation to the reported in the manufacturer datasheet. The estimation of the RT6010 has shown the highest deviation from the documented values, since we obtained estimations for permittivity ranging from 9.8 to 10.8, with the highest incidence around 10 while the manufacturer reports a permittivity of 10.2 to 10.8. It is therefore clear, that although the method shows reliable results for low and medium permittivity materials, it may provide worst estimations for high permittivity low loss materials.

V. CONCLUSION

The method for permittivity estimation proposed here is quite simple to apply and is obtained directly from the equations that characterize printed transmission lines. It is less expensive when compared to other methods which require specific equipment. However, it is only suitable for the measurement of thin dielectrics, since it requires a microstrip line with the test dielectric as substrate.

Although the input impedance should be calculated at a fourth of the resonant frequency, this method allows the calculation of the permittivity at multiple frequencies. Multiples of half of the resonant frequency should be avoided since these will not provide any reasonable value. Still, one must take into account that the losses and therefore the error increases with frequency.

The proposed iterative method for the estimation of the dissipation factor presents better estimations than other commonly used methods at the cost of requiring more calculations. Still, it is shown that the method usually converges after few iterations.

The main drawback of this method is the error, especially in the estimation of higher permittivity low loss dielectrics. Still, the obtained results agree fairly with values reported in datasheets of the considered dielectrics and also with simulation results for printed transmission lines. This means that it can be used to obtain a rough first estimation of an uncharacterized dielectric material that might be used as a substrate for RF circuitry.

As a final remark we can say that the robustness of the method increases if the mean value of multiple measurements on lines with the same substrate is used.

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