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DIELECTRIC PERMITTIVITY MEASURING TECHNIQUE OF FILM-SHAPED MATERIALS AT LOW MICROWAVE FREQUENCIES FROM OPEN-END COPLANAR WAVEGUIDE

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Abstract—This paper presents a broad-band technique for measuring the dielectric permittivity of isotropic nonmagnetic film-shaped materials at low microwave frequencies. The material under test is the substrate of an open-end coplanar waveguide (CPW) used as sample-cell. The dielectric permittivity is extracted from S_{11} reflection parameter measurement of the open-end CPW cell using analytical relationships, which allow to decrease the computation time with respect to any full-wave electromagnetic method. Vector network analyzer (VNA) and high-quality on-coplanar test fixture are used for the measurements between 300 kHz and 3 GHz. Measured ϵ_r data for several nonmagnetic low-loss materials are presented. This technique shows a good agreement between measured and predicted data for the real permittivity over 0.05 GHz–3 GHz frequency range.

1. INTRODUCTION

These last years, various broad-band electromagnetic characterization techniques have been developed in order to cover high microwave frequencies (>3 GHz). Few methods have been carried out for low microwave frequencies (0.3 GHz–3 GHz). The interest in the dielectric properties of nonmagnetic film-shaped materials (ϵ_r) at low microwave frequencies and the lack of methods that can be applied to this material configuration, has led us to develop a broad-band electromagnetic characterization experimental method.

In the literature, we can find many papers about broad-band measuring techniques of electromagnetic properties for solid materials

[1–17]. The microstrip and coplanar transmission lines used as sample-cells seem to adjust better to the electromagnetic characterization of film-shaped materials at low microwave frequencies [9–14]. They do not require great dimensions of the samples to be characterized such as the measurements in the free space [1, 2]. They do not present air gap between the sample and the conductors such as the box-shaped cells [3–6], the open-end waveguide probe [7] or flanged rectangular waveguides [8], since the microstrip and coplanar transmission lines used as sample-cells are produced onto the sample to be characterized. The principal drawback for both sample-cells is the difficulty to measure low-loss materials because of the metallic losses. However, they allow changing its characteristic impedance in order to propagate the quasi-TEM mode and to perform accurate measurements, modifying the width of its conductor strip.

Concerning the determination methods of the electromagnetic properties of materials with microstrip and coplanar cells using a quadripole configuration, it can be seen large errors occur in the measurements at low microwave frequencies (<3 GHz) because of systematic errors [9–14]. At low microwave frequencies, the measured S_{11} parameter magnitude is particularly small and the S_{11} phase uncertainty becomes large causing inaccuracies in the extraction of the electromagnetic properties. In the case of dielectric materials, accurate results can be obtained when the active part length of the cell is several integer multiples of one-half guided wavelength (λ_g). This is also true for other types of characterization methods using box-shaped cells [15]. This requirement on the cell length is not easily achievable when the frequency and the relative permittivity of the material are low. A possible solution for the material characterization at low microwave frequencies would be to fall into a reflection method. On the one hand, it provides information for the deduction of one complex parameter, either permittivity or permeability. In this work, we are interested in measuring electrical properties of nonmagnetic film-shaped materials. On the other hand, the properties of materials for a reflection method are fundamentally deduced from the cell admittance and the wave velocities though the cell and, therefore, the active part length of the cell does not usually come long.

The reflection methods available in the literature use short-circuited microstrip lines or open-end microstrip lines [16, 17]. The short-circuited microstrip line requires via-hole between the strip and ground plane, which is difficult to realize when the substrates are strong as alumina, sapphire, etc. In contrast with this line configuration, an open-end microstrip line needs less technological processing, since it does not require via-hole between the strip and ground plane. Other options are open-circuited or short-circuited CPW lines, which exhibit properties that make them extremely interesting for the electromagnetic characterization of film-shaped materials at low microwave frequencies (<3 GHz). All metallization elements of both CPW lines are on the top of the substrate. No substrate thinning, no backside metallization, and no via-hole are necessary. A given characteristic impedance can be achieved by appropriately selecting the strip width and slot width. Both can be made very small with respect to the substrate thickness. In consequence, the quasi-TEM mode of propagation on a CPW line has a very low dispersion for a large variety of sample-substrates [9, 18].

In this paper, an open-reflection method sensitive to the permittivity measurements, which satisfies the previous requirements about the characterization of nonmagnetic film-shaped materials at low microwave frequencies (<3 GHz), the restriction on the length of the cell and the elimination of backside metallization and via-hole, is developed. Section 2 presents the measuring cell based on an open-circuited CPW line, and the measurement bench covering 300 kHz–3 GHz. An extraction method of the complex permittivity from S_{11} reflection parameter measurement of the open-end CPW cell is proposed in Section 3. The measured complex permittivity values for two nonmagnetic low-loss materials over 300 kHz–3 GHz frequency range from this proposed technique are discussed in Section 4. Finally, conclusions are presented in Section 5.

2. MEASURING CELL AND MEASUREMENT PROCEDURE

The broad-band characterization of film-shaped materials with CPWs can be carried out by means of two types of nonresonant methods: Transmission/reflection method using a quadripole cell and reflection method employing a dipole cell. In [9–15], it can be seen the ransmission/reflection method for the permittiivity extraction of dielectric materials do not work well if the electrical length of the cell is lower than several integer multiples of one-half guided wavelength (λ_g). Thus, a reflection method instead of a transmission/reflection method was chosen in order to increase the accuracy and sensitivity of the permittivity measurement at low microwave frequencies (< 3 GHz). The CPW presents a planar configuration, which allows two types of reflection methods with different termination impedances: open-circuit reflection and short-circuit reflection. Fig. 1 shows the 3-D views of the CPW open-circuit and CPW short-circuit for the corresponding reflection methods. These measuring cells are etched

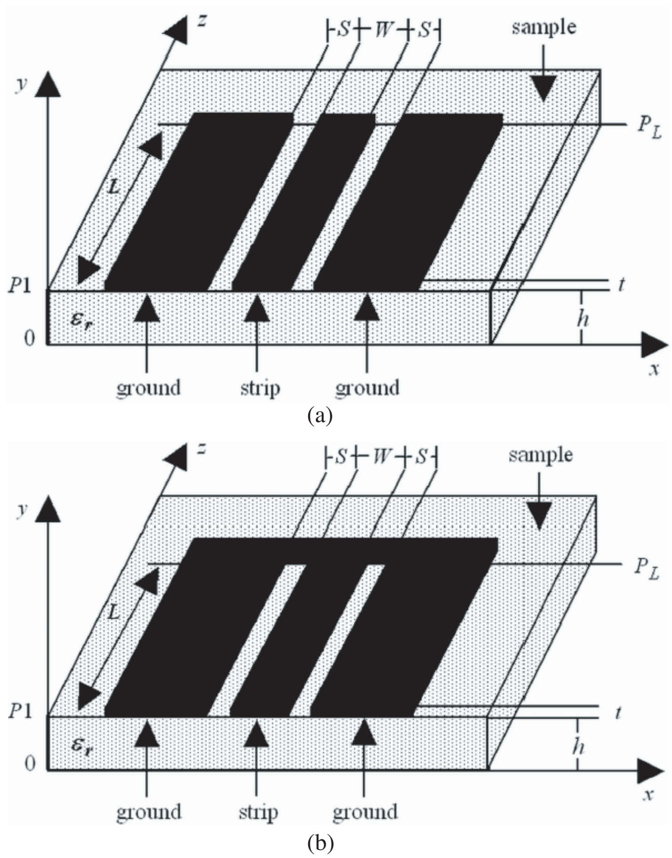

Figure 1. 3-D view of the CPWs with different termination impedances. (a) CPW open-circuit. (b) CPW short-circuit.

onto the sample-substrate to be characterized. In principle, any termination impedance can be used as reflection method. However, at low microwave frequencies, the open-circuit produces a maximum electric field and a minimum magnetic field at the sample-cell, making the open-reflection method particularly suited to the measurement of the electric properties of samples under test. The permittivity of the sample-substrate is obtained from S_{11} reflection parameter measurement with the open-end CPW cell.

The measurement of the open-end CPW cell was performed with the test fixture presented in Fig. 2. S_{11} reflection parameter is measured at the input plane ($P1$) of the open-end CPW cell by means of a VNA (Agilent Technologies E5070B) covering 300 kHz–

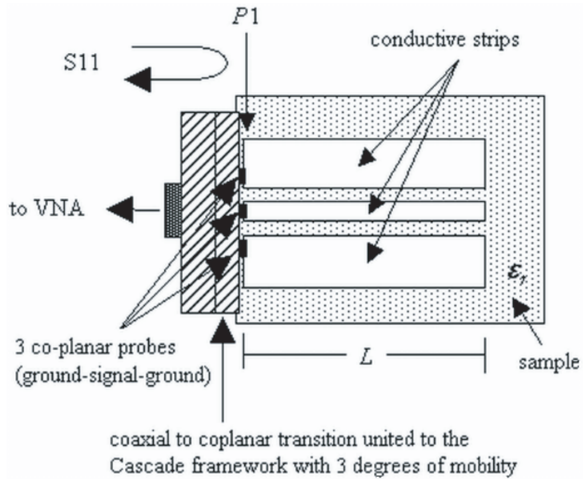

Figure 2. Top view of the test fixture with an open-end CPW cell.

3 GHz and on-coplanar probing system (Cascade Microtech). The on-coplanar probing system allows to connect different sizes of open-end CPW cell to the VNA without thermo-compression between the on-coplanar probing system and the measuring cell. The reference plane ($P1$) is obtained from an initial open-short-load (OSL) calibration covering 300 kHz–3 GHz with a calibration kit of 50 Ω characteristic impedance CPW standard lines. The return losses and repeatability were, respectively, lower than −25 dB and −50 dB over 300 kHz–3 GHz frequency range.

3. DETERMINATION OF THE COMPLEX PERMITTIVITY

The extraction method of the substrate dielectric properties (ϵ_r) for the open-end CPW cell is based on S_{11} parameter measurement achieved at the input plane ($P1$) of the cell under test (Fig. 2), propagating the quasi-TEM mode. The materials to be measured being nonmagnetic, the permeability is fixed to $\mu_r = 1$ in the computation of the permittivity. The extraction method from S_{11} parameter measurement requires an electromagnetic analysis of the open-end CPW cell (direct problem) together with an optimization procedure (inverse problem) to resolve (1) and (2):

$$Y_{im}(f) = Y_0 \frac{1 - S_{11}(f)}{1 + S_{11}(f)} \tag{1}$$

$$Y_{is}(f) = Y_c(f) \coth\left(j\frac{2\pi}{\lambda_0} \sqrt{\epsilon_{reff}(f)}\, L + \Theta(f) \right) \tag{2}$$

with

$$Y_L(f) = Y_c(f) \coth(\Theta(f)) \tag{3}$$

where f is the frequency. $Y_{im}(f)$ and $Y_{is}(f)$ are, respectively, the measured and simulated admittances at the reference plane ($P1$) of the open-end CPW cell (Fig. 2). $Y_L(f)$ is the admittance calculated from analytical relationships at the physical open-end edge [19], as the line P_L shows in Fig. 1(a). $Y_c(f)$ is the characteristic admittance of the open-end CPW cell, which is computed from well known analytical relationships for CPW [20]. $Y_0 = 1/(50\,\Omega)$ is fixed by the measuring system, λ_0 is the vacuum wavelength, and L is the CPW portion line (Fig. 1(a)).

3.1. Direct Problem

The direct problem is the computation of the simulated admittance $Y_{is}(f)$ (Eq. (2)) at the reference plane ($P1$) of the open-end CPW cell (Fig. 2) under test propagating only the quasi-TEM mode, according to the characteristics of the substrate (ϵ_r), the cell dimensions (W, S, t, h, L) and the frequency (f). It requires an electromagnetic analysis of the open-end CPW cell under test. In this paper, CAD models based on analytical relationships were used in order to decrease the computation time with respect to any numerical method. Thus, from a given frequency point (f), a initial complex permittivity value (ϵ_r), and knowing the structure of the cell (W, S, h, L, we assume that the strip and ground planes are perfect and infinitesimally thin conductors, $t = 0\,\mu$m), it is easy to compute the complex effective permittivity ($\epsilon_{reff}(f)$), the characteristic admittance of the open-end CPW cell ($Y_c(f)$) and the admittance at the physical open-end edge

$Y_L(f)$ (Eq. (3)) from CAD models [19, 20]:

$$\epsilon'_{reff}(f) = 1 + \frac{(\epsilon'_r(f) - 1) \cdot K(k') \cdot K(k_1)}{2 \cdot K(k) \cdot K(k'_1)} \tag{4}$$

$$\tan \delta_{deff}(f) = \frac{\epsilon''_{reff}(f)}{\epsilon'_{reff}(f)} = q_{\tan \delta d}(f) \cdot \tan \delta_d(f) \tag{5}$$

$$Y_c(f) = \frac{\sqrt{\epsilon_{reff}(f)}}{30\ \pi} \cdot \frac{K(k)}{K(k')} \tag{6}$$

$$Y_L(f) = \tanh\left(\frac{2\,\pi}{\lambda_0} \cdot \sqrt{\epsilon_{reff}(f)} \cdot \frac{W + 2S}{4}\right) \tag{7}$$

k, k', k_1 and k'_1 are the bounds of the open-end CPW cell structure:

$$k = \frac{W}{W + 2S} \quad \text{and} \quad k_1 = \frac{\sinh\left(\frac{\pi\,W}{4\,h}\right)}{\sinh\left(\pi \frac{W + 2S}{4\,h}\right)} \tag{8}$$

$$k' = \sqrt{1 - k^2} \quad \text{and} \quad k'_1 = \sqrt{1 - k_1^2} \tag{9}$$

$q_{\tan \delta d}$ is the filling factor for dielectric loss tangent [21]:

$$q_{\tan \delta d}(f) = \frac{1 - \frac{1}{\epsilon'_{reff}(f)}}{1 - \frac{1}{\epsilon'_r(f)}} \tag{10}$$

$\tan \delta_d$ is the dielectric loss tangent:

$$\tan \delta_d(f) = \frac{\epsilon''_r(f)}{\epsilon'_r(f)} \tag{11}$$

$K(k)$, $K(k')$, $K(k_1)$ and $K(k'_1)$ are the complete elliptical integrals of first order of modulus k and k_1, and complementary modulus k' and k'_1. These integrals are obtained from analytical relationships [20].

Finally, the admittance $Y_{is}(f)$ is then calculated from (2).

3.2. Inverse Problem

In the previous section, the admittance $Y_{is}(f)$ (Eq. (2)) at the reference plane ($P1$) of the open-end CPW cell (Fig. 2) is determined from the direct problem for a given material ($\epsilon_r(f)$). However, the relation between the admittance $Y_{is}(f)$ and $\epsilon_r(f)$ is not analytic. As a consequence, the calculation of $\epsilon_r(f)$ according to the measured admittance $Y_{im}(f)$ (Eq. (1)) requires the use of an optimization procedure together with the electromagnetic analysis of the open-end CPW cell.

The procedure we have chosen is based on an iterative method derived from the gradient method [22]. It consists in defining an initial vector P_0 from an initial value of $\epsilon_r(f)$ as for example the vacuum electromagnetic properties ($\epsilon_r(f) = 1 - j\,0$):

$$P_0 = \begin{bmatrix} \epsilon_r^{'} = 1 \\ \epsilon_r^{''} = 0 \end{bmatrix} \tag{12}$$

Then, an error vector ΔY is determined as follows:

$$\Delta Y = \begin{bmatrix} f_1(\epsilon_r^{'}, \epsilon_r^{''}) = \Re(Y_{im}(f) - Y_{is}(f, \epsilon_r^{'}, \epsilon_r^{''})) \\ f_2(\epsilon_r^{'}, \epsilon_r^{''}) = \Im(Y_{im}(f) - Y_{is}(f, \epsilon_r^{'}, \epsilon_r^{''})) \end{bmatrix} \tag{13}$$

where Y_{is} is the theoretical admittance (Eq. (2)) of the open-end CPW cell calculated for the initial value of $\epsilon_r(f)$. If each variable ($\epsilon_r^{'}$, $\epsilon_r^{''}$) is incremented by small values ($\epsilon_r^{'} + d\,\epsilon_r^{'}$, $\epsilon_r^{''} + d\,\epsilon_r^{''}$), then the functions f_1 and f_2 may be written in Taylors series as:

$$\begin{aligned} f_1(\epsilon_r^{'} + d\,\epsilon_r^{'},\, \epsilon_r^{''} + d\,\epsilon_r^{''}) &= f_1(\epsilon_r^{'},\, \epsilon_r^{''}) + \frac{\partial f_1}{\partial\,\epsilon_r^{'}}\, d\,\epsilon_r^{'} + \frac{\partial f_1}{\partial\,\epsilon_r^{''}}\, d\,\epsilon_r^{''} \\ &\quad + O((d\,\epsilon_r^{'})^2,\, (d\,\epsilon_r^{''})^2) \\ f_2(\epsilon_r^{'} + d\,\epsilon_r^{'},\, \epsilon_r^{''} + d\,\epsilon_r^{''}) &= f_2(\epsilon_r^{'},\, \epsilon_r^{''}) + \frac{\partial f_2}{\partial \epsilon_r^{'}}\, d\,\epsilon_r^{'} + \frac{\partial f_2}{\partial \epsilon_r^{''}}\, d\,\epsilon_r^{''} \\ &\quad + O((d\,\epsilon_r^{'})^2,\, (d\,\epsilon_r^{''})^2) \end{aligned} \tag{14}$$

where $O((d\,\epsilon_r^{'})^2,\, (d\,\epsilon_r^{''})^2)$ are the higher order terms in Taylors series. If the increments of ($\epsilon_r^{'}$, $\epsilon_r^{''}$) by small values ($\epsilon_r^{'} + d\,\epsilon_r^{'}$, $\epsilon_r^{''} + d\,\epsilon_r^{''}$) are such that $f_1(\epsilon_r^{'} + d\,\epsilon_r^{'},\, \epsilon_r^{''} + d\,\epsilon_r^{''})$ and $f_2(\epsilon_r^{'} + d\,\epsilon_r^{'},\, \epsilon_r^{''} + d\,\epsilon_r^{''})$ are simultaneously zero, then the following matrix equation can be written:

$$\Delta Y = -[G]\Delta P \tag{15}$$

where

$$[G] = \begin{bmatrix} \dfrac{\partial f_1}{\partial\,\epsilon_r^{'}} & \dfrac{\partial f_1}{\partial\,\epsilon_r^{''}} \\ \dfrac{\partial f_2}{\partial\,\epsilon_r^{'}} & \dfrac{\partial f_2}{\partial\,\epsilon_r^{''}} \end{bmatrix} \quad \text{and} \quad \Delta P = \begin{bmatrix} d\,\epsilon_r^{'} \\ d\,\epsilon_r^{''} \end{bmatrix} \tag{16}$$

The components of the gradient matrix $[G]$ are calculated using (1) to (11) (direct problem). Finally, a new direction is obtained:

$$P_n = P_{n-1} + \Delta P \quad \text{and} \quad \Delta P = -[G]^{-1}\Delta Y \tag{17}$$

This procedure is repeated until required convergence is obtained: $\| \Delta Y \|$ is lower than 10^{-6}. Different test have confirmed the validity of this procedure and the unique solution in 300 kHz–3 GHz frequency range.

4. EXPERIMENTAL RESULTS

For the purpose of validating this open-reflection electromagnetic characterization method, two dielectrics with well-known properties were measured from 300 kHz to 3 GHz: Alumina ($\epsilon_r^{'} = 9.85$, $\epsilon_r^{''} < 0.001$ at 10 GHz) shown in Fig. 3 and RT/duroid 6006 ($\epsilon_r^{'} = 6.15$, $\epsilon_r^{''} < 0.017$ at 10 GHz) presented in Fig. 4. In these figures, we have also represented the maximum uncertainties (dotted lines) over the

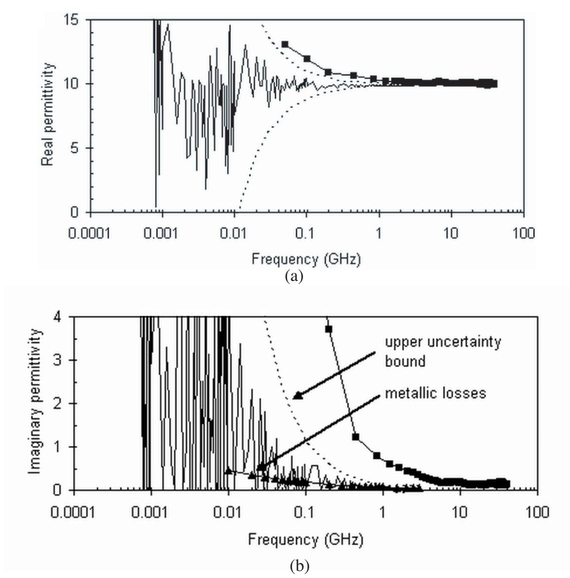

Figure 3. Measured ϵ_r data for alumina from open-end CPW cell. (a) Real permittivity. (b) Imaginary permittivity. —— Measured values with the proposed method, ■ values obtained from [9], - - - lower and upper maximum uncertainties bounds caused by the VNA for $\epsilon_r = 9.85 - j0$ and ▲ metallic losses.

imaginary and real permittivities for $\epsilon_r = 9.85 - j\,0$ and $\epsilon_r = 6.15 - j\,0$ linked to measurement uncertainties caused by the VNA (Agilent Technologies E5070B) [15], and the metallic losses (▲) due to the conductors of the open-end CPW cells. The metallic losses have been simulated from commercial full-wave electromagnetic simulator based on finite element method between 0.01 GHz and 3 GHz, and normalized with respect to the magnitude ϵ'' such as [21]:

$$\epsilon_c'' = \frac{\alpha_c(f)\,\epsilon_r'(f)}{0.91\,\sqrt{\epsilon_{reff}'(f)}\,f\,q_{\tan\delta d(f)}} \tag{18}$$

where α_c is the attenuation of the conductor losses (Np/cm), f is the frequency (GHz) and $q_{\tan\delta d}$ is defined in (10).

The dimensions of the open-end CPW cells are: $W = 50\,\mu$m, $W + 2S = 175\,\mu$m, $h = 635\,\mu$m, $t = 5\,\mu$m (gold) and $L = 10$ mm for alumina, and $W = 75\,\mu$m, $W + 2S = 175\,\mu$m, $h = 640\,\mu$m, $t = 8\,\mu$m (copper) and $L = 10$ mm for RT/duroid 6006.

The graphs of ϵ_r' for both dielectrics (Figs. 3(a) and 4(a)) fall within the uncertainty bounds and the measured values are in close agreement with those anticipated at frequencies above 0.05 GHz. The mean errors from 0.05 GHz to 3 GHz for alumina and RT/duroid 6006 are 0.7% and 1.1%, respectively, with respect to the manufacturer values. In Fig. 3(a), it can be seen this open-reflection method is more accurate than transmission/reflection technique using a quadripole CPW cell with alumina substrate [9], which presents a mean error of 8.6% between 0.05 GHz and 3 GHz.

The measured losses (ϵ_r'') for alumina (Fig. 3(b)) and RT/duroid 6006 (Fig. 4(b)) do not correspond with the manufacturer values. On the other hand, accurate measurements of ϵ_r'' for alumina can not be carried out either with the transmission/reflection technique using a quadripole CPW cell, as shown in Fig. 3(b) [9]. However, the measured losses and simulated metallic losses from open-end CPW cells are within the uncertainties bounds. This means that the measured metallic and dielectric losses are lower than the maximum measurement uncertainties caused by the VNA. Therefore, it is not possible to estimate the magnitude of the dielectric losses. Only materials with dielectric losses higher than the metallic losses of the cell, radiation losses, the repeatability errors and measurement uncertainties due to the measurement bench can be measured with accuracy. For the measured materials, the loss tangent values must be higher than those represented in Fig. 5.

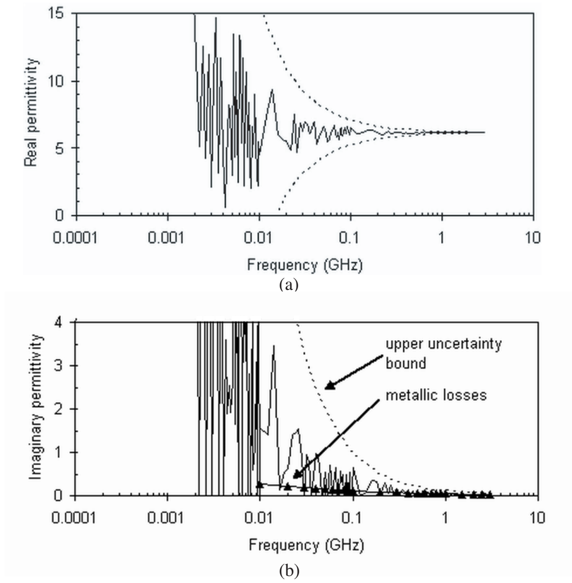

Figure 4. Measured ϵ_r data for RT/duroid 6006 from open-end CPW cell. (a) Real permittivity. (b) Imaginary permittivity. —— Measured values with the proposed method, - - - lower and upper maximum uncertainties bounds caused by the VNA for $\epsilon_r = 6.15 - j0$ and ▲ metallic losses.

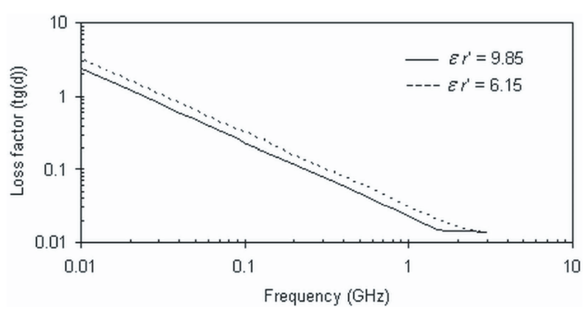

Figure 5. Evolution of the loss tangent bounds for two real permittivity values versus frequency linked only to maximum measurement uncertainties caused by the VNA (Agilent Technologies E5070B) [15].

5. CONCLUSION

In this paper, we have presented a broad-band electromagnetic characterization technique for measuring isotropic nonmagnetic film-shaped materials at low microwave frequencies. It is based on a reflection method, which uses an open-end CPW line as sample-cell. The open-end CPW cell is etched onto the sample to be characterized. The extraction method of the substrate permittivity (ϵ_r) is obtained from S_{11} parameter measurement and a processing method using a fast electromagnetic analysis of the open-end CPW cell based on analytical relationships taking into account the quasi-TEM mode together with an optimization procedure based on a gradient method. A measurement bench using an on-coplanar test fixture connected to a vector network analyzer is employed for the S_{11} reflection parameter measurement at the unique access plane of the open-end CPW cell. The experimental results have shown the validity of this open-reflection method for the real permittivity measurements of dielectric materials at low microwave frequencies (0.05 GHz–3 GHz). The dielectric losses can be measured for samples with losses higher than the metallic losses, the radiation losses, the repeatability errors and the measurement uncertainties caused by the measurement bench. This technique can yield accurate measurements of the permittivity for isotropic dielectric materials with electromagnetic applications at low microwave frequencies (0.3 GHz– 3 GHz).

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