S-Parameter Broad-Band Measurements On-Microstrip and Fast Extraction of the Substrate Intrinsic Properties

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***Abstract*—A broad-band technique for determining the electromagnetic properties of isotropic film-shaped materials, which uses a microstrip line, is presented. Complex permittivity and permeability are computed from analytical equations and S-parameter measurements of microstrip cells propagating the dominant mode. Measured ε_r and μ_r data for several materials are presented between 0.05 GHz and 40 GHz. This technique shows a good agreement between measured and predicted data.**

***Index Terms*—Broad-band measurement, microstrip, permeability, permittivity, propagation, S-parameters.**

I. INTRODUCTION

PERMITTIVITY and permeability measurements in a microwave frequency range are required in numerous applications for a large variety of film-shaped materials. Contrary to the box-shaped broad-band cells (coaxial, rectangular waveguide or stripline device) [1]–[3], the coplanar and microstrip lines used as sample cells do not present air gaps between the sample and the conductors, since they are produced onto the sample to be characterized. Moreover, they allow film-shaped materials to be characterized and the characteristic impedance to be changed by modifying the conductive strip width. Thus, it is possible to optimize their shapes in order to propagate the dominant mode (quasi-TEM) and to perform accurate S-parameter measurements with the same cell in a broad-band of frequencies. Among both cells, the microstrip cell seems to be that most suited to the electromagnetic characterization of materials, since it allows a better concentration of the fields into the dielectric and magnetic materials, and lower metallic losses than the coplanar cell. Among the developed characterization methods using microstrip, only the substrate dielectric properties have been determined [4], [5]. The characterization method for magnetic substrates using microstrip is incomplete and it is our purpose to present one in a form most useful to the engineering community.

In this letter, an easy and fast processing method of the S-parameters measured from microstrip cells for determining simultaneously the complex permittivity and permeability of the microstrip substrates is proposed. It is based on the quasi-TEM mode propagation. Analytical equations compute the propagation constant and characteristic impedance of the microstrip cell instead of any numerical method, which decreases considerably the computation time. The S-parameter measurement bench employs a vector network analyzer and a high-quality test fixture on-microstrip covering 0.05–40 GHz.

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II. PROCESSING METHOD

The processing method is based on the S-parameter measurements at the microstrip access planes. It requires the propagation to be the quasi-TEM dominant mode. In this case, it is possible to write simple formulas for the characteristic impedance Z_c, propagation constant γ, and total effective loss tangent $\operatorname{tg}\delta_{\text{eff}}$ for microstrip on a substrate exhibiting both dielectric and magnetic properties [6]

$$Z_c = Z_0' \sqrt{\frac{\mu_{r\,\text{eff}}}{\varepsilon_{r\,\text{eff}}}} \tag{1}$$

$$\gamma = \omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon_{r\,\text{eff}}\mu_{r\,\text{eff}}} \tag{2}$$

$$\operatorname{tg}\delta_{\text{eff}} = q_{\operatorname{tg}\delta d}\cdot\operatorname{tg}\delta_d + q_{\operatorname{tg}\delta m}\cdot\operatorname{tg}\delta_m \tag{3}$$

where

$$\begin{aligned}\operatorname{tg}\delta_d &= (\varepsilon_r''/\varepsilon_r');\\ \operatorname{tg}\delta_m &= (\mu_r''/\mu_r');\\ q_{\operatorname{tg}\delta d} &= (1-(\varepsilon_{r\,\text{eff}}')^{-1})/(1-(\varepsilon_r')^{-1});\\ q_{\operatorname{tg}\delta m} &= (1-\mu_{r\,\text{eff}}')/(1-\mu_r')\end{aligned}$$

where Z_0' is the characteristic impedance when $\varepsilon_r = \mu_r = 1$, which is computed from an analytical equation [7].

The S-parameter measurement processing requires a microstrip-cell electromagnetic analysis (direct problem) together with an optimization procedure (inverse problem). The direct problem consists in computing the S-parameters at the access planes of the microstrip cell under test propagating only the quasi-TEM mode, according to the complex substrate properties (ε_r, μ_r), the cell dimensions and the frequency. Analytical equations instead of any numerical method were used in order to decrease the computation time. In the magnetic material case, the analytical equations are obtained by a duality relationship. The duality consists to realize the conversions $\varepsilon_r \rightarrow (1/\mu_r)$ and $\varepsilon_{r\,\text{eff}} \rightarrow (1/\mu_{r\,\text{eff}})$ in the analytical equation for the dielectric case [6]. It follows from analytical equations for the dielectric case [7], [8] that the static effective equation and the dispersion function for the magnetic case can be defined as

$$\mu'_{r\,\mathrm{eff,stat}} = \left\{ \left[\frac{(\mu'_r)^{-1}+1}{2} \right] + \left[\frac{(\mu'_r)^{-1}-1}{2} \right] \cdot \left[1 + \frac{10h}{W} \right]^{-ab} \right\}^{-1} \tag{4}$$

$$\mu'_{r\,\mathrm{eff}}(f) = \left[(\mu'_r)^{-1} - \left(\frac{(\mu'_r)^{-1} - (\mu'_{r\,\mathrm{eff,stat}})^{-1}}{1+P} \right) \right]^{-1} \tag{5}$$

where

$$\begin{aligned} a &= 1 + \frac{1}{49} \ln \left[\frac{(W/h)^4 + (W/52h)^2}{(W/h)^4 + 0.432} \right] \\ &\quad + \frac{1}{18.7} \ln[1 + (W/18.1h)^3], \\ b &= 0.564 \left[(\mu'_r)^{-1} - 0.9/(\mu'_r)^{-1} + 3 \right]^{0.053} \\ P &= P_1 \cdot P_2 \cdot [(0.1844 + P_3 \cdot P_4) \cdot 10 \cdot f \cdot h]^{1.5763} \\ P_1 &= 0.274\,88 + (W/h) \\ &\quad \cdot \lfloor 0.6315 + (0.525/(1 + 0.157 \cdot f \cdot h)^{20}) \rfloor \\ &\quad - 0.065\,683 \cdot \exp(-8.7513 \cdot (W/h)) \\ P_2 &= 0.336\,22 \cdot \lfloor 1 - \exp(-0.034\,42/\mu'_r) \rfloor \\ P_3 &= 0.0363 \cdot \exp(-4.6 \cdot W/h) \\ &\quad \cdot \lfloor 1 - \exp(-(f \cdot h/3.87)^{4.97}) \rfloor \\ P_4 &= 1 + 2.751 \cdot [1 - \exp(-(\mu'_r \cdot 15.916)^{-8})]. \end{aligned}$$

h is in cm and f is in GHz in the P, P_1–P_4 terms.

From given complex ε_r and μ_r values, a given frequency point, and knowing the microstrip-cell structure, it is easy to compute the static effective permittivity and permeability, then the complex propagation constant γ and the complex characteristic impedance Z_c of the microstrip cell from the analytical equations defined in [7], [8] and (1)–(5). Then, the S-parameters are computed by the reflection/transmission method [1], [2]. Only the S_{11} and S_{21} complex parameters are taken into account, since the measured microstrip cell is symmetrical and passive. The optimization procedure (the inverse problem) is based on an iterative method derived from the gradient method [3], [9]. It simultaneously carries out the ε_r and μ_r computation and the convergence between (S_{11}, S_{21}) measured values and those computed by the analytical equations (the direct problem) through the successive increment of any ε_r and μ_r initial values.

III. Measurements and Results

The microstrip measurements were realized with the HP85107 network analyzer connected to the on-microstrip (Wiltron 3680 K) probing station (Fig. 1) covering 0.05–40 GHz. This test fixture allows different sizes of microstrip, measurements easy to implement, repeatable, and accurate, thanks to a calibration procedure. It uses a calibration Kit of 50 Ω characteristic impedance with standard microstrip lines of alumina substrate. It employs a Line-Reflect-Match (LRM) and Line-Reflect-Line (LRL) covering 0.05–2 GHz and 2–40 GHz, respectively. The two achieved measurement reference planes (P_1, P_2) are at the two probe outputs. Return losses, insertion losses and repeatability were better than -20 dB, -2 dB, and ± 0.2 dB, respectively, over the entire 0.05–40 GHz frequency range.

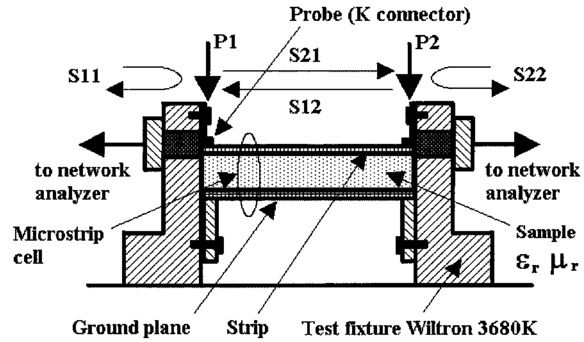

Fig. 1. Representation of the test fixture Wiltron 3680 K with a microstrip cell.

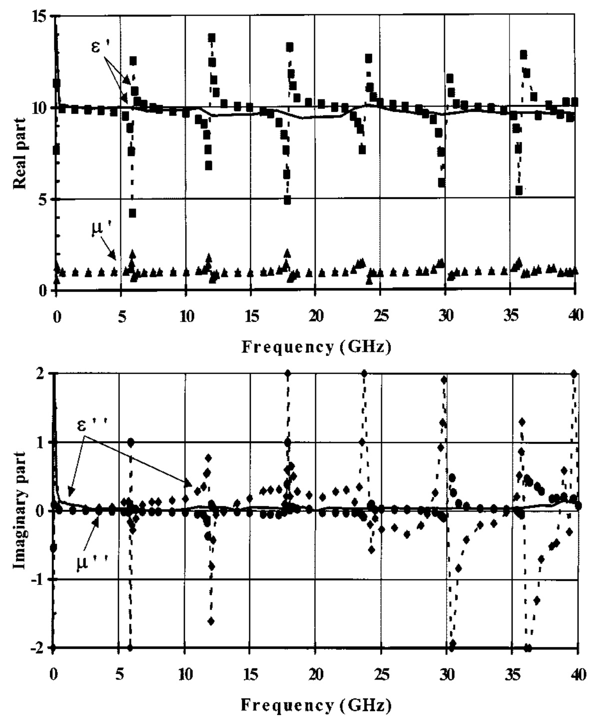

Fig. 2. Measured ε_r and μ_r data for alumina ($t = 5\ \mu$m of gold, $W = 200\ \mu$m, $h = 254\ \mu$m, $d = 1$ cm). (a) ———— ε'_r value ($\mu_r = 1 - j0$ fixed in the processing method), -■—■—■— ε'_r value, –△—△—△— μ'_r value, (b) ———— ε''_r value ($\mu_r = 1 - j0$ fixed in the processing method), -◇—◇—◇— ε''_r value, - ● — ● — ● — μ''_r value.

To illustrate this characterization method, microstrip cells were made from thin-film technology) [10] on an alumina ($\varepsilon'_r = 9.85, \varepsilon''_r < 0.001$ at 10 GHz, $\mu_r = 1$) sample with well-known dielectric properties and a unknown heterogeneous magnetic sample. The cells are configured using the following constraints in the measurement frequency band in order to propagate the quasi-TEM mode and to neglect substrate surface waves [10] $W \ll \lambda_0, W/h < 1$ and $h/\lambda_0 \ll 1$ (W, h and λ_0 are the strip width, substrate thickness and wavelength in free space, respectively). The measurements performed on each of these materials were obtained at room temperature and they are represented in Figs. 2 and 3. The accuracy on the complex ε_r and μ_r computation is linked to the uncertainties

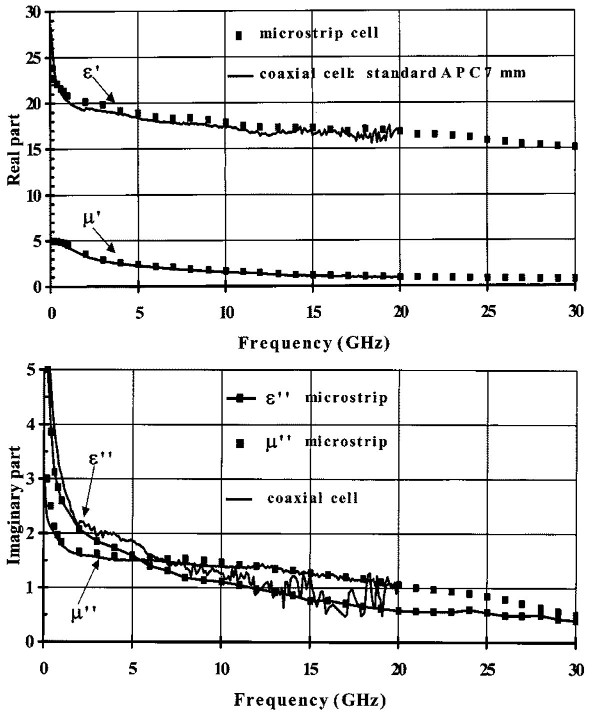

Fig. 3. Complex measured ε_r and μ_r data for a heterogeneous magnetic material in the 0.05 to 30 GHz frequency range using microstrip ($t = 5$ μm of gold, $W = 210$ μm, $h = 280$ μm, $d = 6$ mm) and coaxial (APC 7 mm) cells. ——— Measured data with a coaxial APC 7 mm cell. -■—■—■— Measured data with a microstrip cell.

on the S-parameter measurements and the sample-cell length. A detailed error bound analysis of this method based from [11] is presented in [12]. The measured ε_r' and μ_r' values for alumina [Fig. 2(a)] correspond to those anticipated (except the peaks). In order to suppress inaccurate peaks due to the periodic behavior of the sample-cell with the frequency (especially when substrate is loss less), and to obtain accurate results on the complex permittivity values of nonmagnetic materials, we fixed $\mu_r = 1 - j0$ in the processing method as in [11]. Thus, the ε_r' values for alumina (solid lines) have an error better than 3% in comparison with the manufacturer value. In the case of losses, large errors are also shown for alumina with $\mu_r = 1$ fixed (Fig. 2(b) solid line). These errors are mainly due to the network analyzer, the test fixture performance, and the whole microstrip cell (dielectric, metallic, and radiation) losses. The measurement of low-loss samples as alumina is not possible with this technique. To obtain reasonable accuracy on ε_r'' and μ_r'', the sample losses must be higher than the metallic and radiation losses and the repeatability errors of the test fixture. Only in this case, the metallic and radiation losses can be differentiated of the material losses in order to be subtracted or omitted of the measured whole losses, as for the microstrip cell loaded with a heterogeneous magnetic sample that follows. The metallic (if $t \gg 3\delta, t$ conductor thickness, δ skin depth) and radiation losses can be faster estimated from analytical equations [13], [14]. The analytical equations for the magnetic substrate case are obtained with the above duality relationship [6].

Measured ε_r and μ_r values for a heterogeneous magnetic sample with a microstrip cell are shown in Fig. 3 with squares. They are compared with those obtained by another well-known method using an APC 7 mm standard coaxial cell [1]. The measured values from the coaxial cell are drawn with continuous lines. As it can be seen, they exhibit the same properties than those obtained with the microstrip cell. Moreover, it is possible to confirm the diamagnetic property of this material thanks to the possibility to increase in frequency with the microstrip cell.

IV. Conclusion

A broad-band characterization technique of isotropic film-shaped materials has been developed. It uses a microstrip line as cell, which does not present air gaps. Moreover, its characteristic impedance can be optimized in order to propagate the dominant mode and to realize accurate measurements. The complex properties (ε_r, μ_r) are easily computed from a fast-processing method of the S-parameters using analytical relationships. The S-parameters are measured at the microstrip access planes with a network analyzer and test fixture on-microstrip. Some measured data for a standard dielectric and heterogeneous magnetic material have demonstrated the validity of this method. This technique should be suitable for other materials with electromagnetic applications in the 0.05 GHz to 40 GHz frequency range.

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