A Broadband Permeameter for "*in situ*" Measurements of Rectangular Samples

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***Abstract*—The measurement method presented here permits the determination of the complex permeability μ^* and permittivity ε^* of rectangular samples of various thicknesses (0.1 μm–1800 μm) over the (130 MHz–7 GHz) frequency band. This method is based on the S-parameters measurements of an asymmetrical stripline containing the sample under test. It does not require any magnetic reference sample. The originality of this method is to reproduce the same environment for the material under test as encountered in microwave devices. The results given by this "*in situ*" measurement technique are more useful to design microwave devices than those given by traditional measurement methods.**

***Index Terms*—Magnetic materials, permeability measurement, stripline, thin films.**

I. INTRODUCTION

DISPERSION properties of magnetic materials are widely used in many microwave circuits such as circulators, phase shifters and filters. Important parameters that enter into the design of these devices are the gyromagnetic resonance frequency and the values of the complex permeability and permittivity over a broad frequency band. For isotropic materials, a large number of characterization techniques have been developed in the last few years [1]–[4]. One of the most widespread technique is the coaxial line method [1]. The permeability of the material cannot always be considered as intrinsic parameter due to demagnetizing fields. Indeed, the sample shape and the applied constraints (magnetizing field) affect these parameters. For example, the measured permeability of ferrites in a rectangular waveguide differs from that measured in a coaxial line. Materials with structural anisotropy also present variations of the measured parameters depending on the wave polarization [5]. So, the determination of the material permeability, including the effect of demagnetizing fields, is essential in the design of microwave magnetic circuits. In this context, "*in situ*" characterization methods are necessary in such a way that the measurement device reproduces the electromagnetic environment of the microwave device: the field pattern of the microwave device and the material location in the device.

As planar propagation structures (coplanar and microstrip lines) are widely used in communication systems, planar transmission line methods have been explored. Among the existing characterization methods, several test devices have mainly held our attention. Barry has proposed a stripline method [2] where permeability and permittivity measurements are possible over a broad frequency band. In this configuration, the cross section must be fully filled with the sample and demagnetizing fields are not taken into account. Another method, based on the magnetic flux measurement in a single coil, enables only permeability measurement [3]. This technique requires a magnetic reference sample to calibrate the cell. Multilayered materials characterization is not allowed. The microstrip line method is the most interesting technique in our case [4]. A rectangular sample, which does not fill the cell cross section, is laid on the conducting strip. This method, which takes demagnetizing fields into account, gives the complex permeability and permittivity values over a broad frequency band. A full wave analysis is used for the electromagnetic analysis of the cell. It permits a thorough description of the dynamic behavior of the cell but the data processing program is complex. The major drawback of the method is the storage of an important part of the microwave energy in the alumina substrate implying a decrease of the sensitivity of the test device. In this paper, an asymmetrical stripline shown in Fig. 1 is developed in order to increase the sensitivity of the test device. Permeability and permittivity measurements of multilayered materials and thin films are allowed over a broad frequency band. Details on the electromagnetic analysis of the device and experimental "*in situ*" measurements of permeability will be presented.

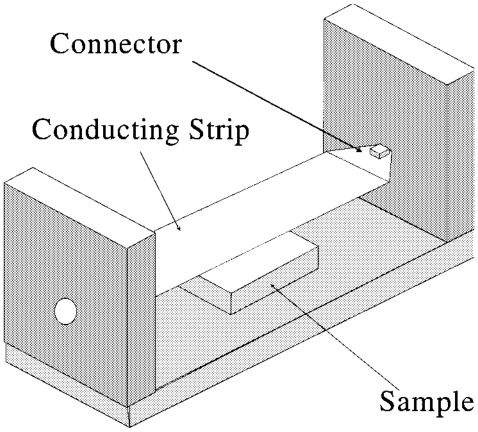

Fig. 1. Schematization of the cell without the upper ground plane. The sample is laid on the ground plane.

II. ELECTROMAGNETIC ANALYSIS OF THE CELL

Due to the heterogeneity of the loaded cross section (Fig. 2), no analytical expressions exist to calculate the electromagnetic parameters (ε^*, μ^*) of the material from the measured parameters. Then, two steps are necessary for this determination: Firstly, the electromagnetic analysis of the test device must be

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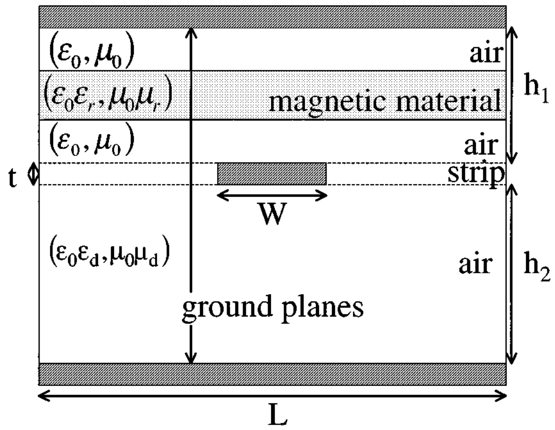

Fig. 2. Asymmetrical stripline cross section containing the material under test.

performed and, secondly, the resolution of the inverse problem must be addressed. The calculation of the effective constants of the transverse section from complex permeability and permittivity of the sample is the direct problem. The inverse problem consists in matching theoretical and measured results in order to extract the complex permeability and the permittivity of the material.

A. The Quasistatic Theory—The Direct Problem

Fig. 2 shows the transverse section of the test device. Four layers compose the cross section. This configuration enables us to take different locations of the material into account. Either the material is laid on the ground plane (Fig. 1), or the sample is laid on the strip (Fig. 2) to increase the cell sensitivity. An air gap between the material and its support is taken into account to represent the experimental conditions. Because of the heterogeneity of the cross section, a transverse electromagnetic (TEM) wave cannot be propagated. However, for low frequencies, longitudinal components of the microwave fields can be neglected compared with transversal ones. So, the hypothesis of a quasi-TEM mode is valid. Moreover, as there is no substrate, the validity domain of this approximation is justified in the centimeter wave band. An homogenization of the propagation structure has been realized. The quasistatic theory has been used to determine the inductance (L) and the capacitance (C) per unit of length of the line. This approach, based on the Green's potential functions and on the transverse transmission line method, allows, for multilayered dielectrics, the calculation of the characteristic impedance and of the propagation constant of a transmission line [6]. Based on the Kaneki's relations, this approach can be used for magnetic media [7]. Under these assumptions, the theoretical effective permeability (μ_{eff}^{th}) and permittivity ($\varepsilon_{\text{eff}}^{th}$) of the cross section loaded by a sample have been calculated. Impedance expressions of the loaded and of the unloaded cells are compared to extract the effective constants (1) as function of (L, C) and (L_0, C_0). (L_0, C_0) are inductance and capacitance per unit of length calculated in the cell without the sample.

$$\mu_{\text{eff}}^{th} = \frac{L}{L_0} \quad \text{and} \quad \varepsilon_{\text{eff}}^{th} = \frac{C}{C_0}. \tag{1}$$

B. Optimization Method—Inverse Method

The first step of the inverse problem is to determine the measured effective constants (μ_{eff}^{m}, $\varepsilon_{\text{eff}}^{m}$) of the cross section as a function of the frequency. Since the dominant mode is quasi-TEM, the effective electromagnetic parameters are determined from S-parameters using the Nicolson/Ross procedure [8]. In this method, the equations for the scattering parameters are combined to lead to an explicit equation for the effective permeability and permittivity.

As there are no analytical expressions to determine the electromagnetic constants (μ^*, ε^*) of the sample, the second step of the data processing procedure consist in extracting these parameters from the measured effective constants. Complex electromagnetic parameters of the material are calculated by matching theoretical and measured effective values. Errors equations (2) for the complex permeability and permittivity of the material are solved using a dichotomous procedure in the complex plane.

$$\begin{cases} F(\mu', \mu'') = \left|\mu_{\text{eff}}^{m} - \mu_{\text{eff}}^{th}\right|^2 \\ G(\varepsilon', \varepsilon'') = \left|\varepsilon_{\text{eff}}^{m} - \varepsilon_{\text{eff}}^{th}\right|^2 \end{cases}. \tag{2}$$

III. EXPERIMENTAL RESULTS

A. Experimental Test Device

The measurement cell (Fig. 1) is an asymmetrical stripline ended by two tapers. These discontinuities, taken into account in the calibration procedure, are made to avoid capacitances between the conducting strip ($t = 0.5$ mm, $W = 9$ mm) and conductor planes where SMA connectors are fixed. The nonequidistance between the strip and the ground planes ($h_1 = 1.8$ mm, $h_2 = 10$ mm) is made to approach microstrip configuration. The electromagnetic energy is mainly confined in the space located between the strip and the nearest ground plane. No laterally conductive walls are necessary because the ground plane width ($L = 30$ mm) is wider than three time the separation between the strip and the nearest ground plane (h_1).

The S-parameters measurements are performed with a 8720A Hewlett-Packard network analyzer system in the (130 MHz–7 GHz) frequency range. The first step in the measurement procedure is to compensate for errors associated with the S-parameter test set, cables and stripline device (in particular tapers and impedance mismatch). In the SOLT calibration procedure, the test device is used during the reflection-transmission correction ("THRU") in order to eliminate errors due to the device [4]. The acquisition of the data is realized with a personal computer and Labview language is utilized to program the optimization method.

B. Results

Results presented in this section were obtained with a sample directly laid on the conducting strip. To confirm the validity of the quasistatic approach, dielectric materials of well-known properties have been tested. Expected values of permittivity and permeability have been obtained. To highlight the advantages of this measuring cell to integrate characterized materials in microwave devices, several samples (length $= 8$ mm) of various

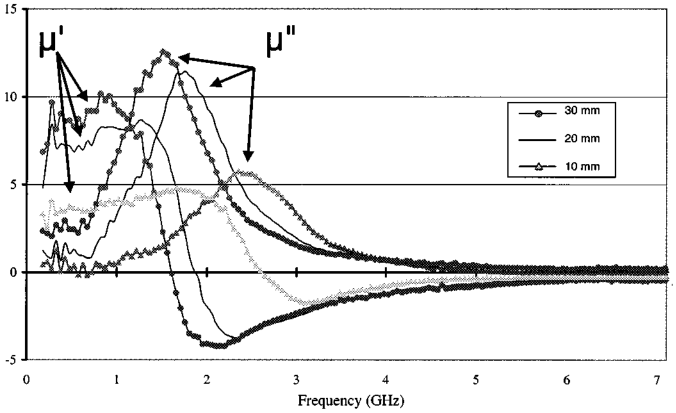

Fig. 3. Measured μ^* data as function of frequency for a ferrocomposite material of various widths.

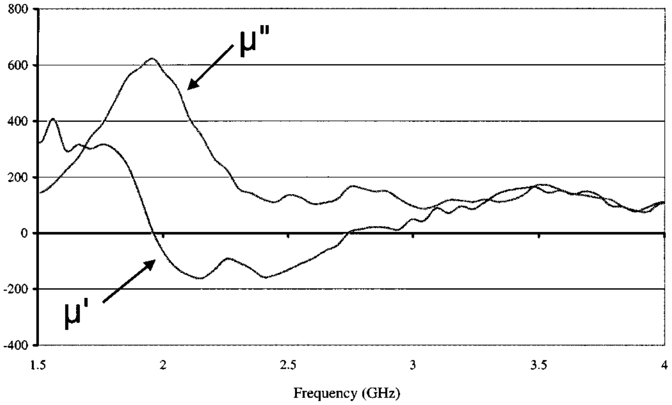

Fig. 4. Measured μ^* data as function of frequency for a ferromagnetic thin film (thickness is 0.154 μm).

widths are tested. The material is a ferromagnetic composite which presents a strong anisotropy of structure [5]. It consists of laminations of ferromagnetic (CoNbZr, thickness $= 0.43\ \mu$m) and insulating (Kapton, thickness $= 12.7\ \mu$m) layers. Measured of permeability data of the composite is given in Fig. 3. A decrease of the permeability level and a shift of the gyromagnetic resonance frequency are observed when the material width decreases. Permeability level is in good agreement with theory. Gilbert's theory and Wiener's approximation allow the determination of the static permeability level. Indeed, the saturation magnetization ($4\pi M_S = 11\,300$ G), the anisotropic field ($H_a = 34$ Oe) of a ferromagnetic layer and the volumetric fraction in ferromagnetic material ($q = 2.51\%$) give a permeability level of approximately 9.5. The theoretical value, which gives an upper limit, and measured one ($\mu' = 9$) for the widest sample are close to each other. Demagnetizing fields, which are more important when the material width is small, explain the decrease of the permeability level. The shift of the ferromagnetic resonance frequency is also due to the demagnetizing fields. The origins of the microwave demagnetizing fields are poles created by the microwave magnetic field at the surface of the ferrocomposite.

Fig. 4 shows measurement of the permeability of a rectangular thin film (thickness of 0.154 μm, length $=$ 8 mm, width $=$ 9 mm) deposited on a rigid substrate (glass with thickness of 1.5 mm). Measured static permeability is in good agreement with theory ($4\pi M_s = 11\,100$ G, $H_a = 34$ Oe) since a theoretical value of 350 is expected with the Gilbert's theory.

IV. CONCLUSION

The feasibility of a broadband permeameter is described in this paper. Permittivity measurements are also simultaneously accessible. For the material under test, the electromagnetic configuration is the same than those encountered in microwave circuits. The quasistatic approach of the test device is quite sufficient to calculate magnetic and dielectric constants in the 130 MHz–7 GHz frequency range. Measurements are compared with theoretical results, and are found to be in good agreement. The results confirm the feasibility and the sensitivity of this technique.

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