Automatic Measurement of Complex Tensorial Permeability of Magnetized Materials in a Wide Microwave Frequency Range

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***Abstract*—This paper describes a microwave measurement technique enabling the automatic and broad-band determination of the complex permeability tensor components μ, κ of magnetized materials. The method is applicable to ferrites, as well as magnetic composite materials. The measurement cell is composed of a nonreciprocal strip transmission line partly filled with the sample that is to be characterized. The data-processing program based on a quasi-static approach is valid whatever the magnetization state of the material is from the total demagnetization state to the saturation. The scattering matrix of the cell is measured in a wide frequency range (130 MHz–6 GHz) with a network analyzer setup. The stripline is set in the air gap of an electromagnet to magnetize the material. The electromagnetic parameters of the sample under test are deduced from the scattering matrix using analytical relations. General equations for μ and κ are proposed. Some measurements of magnetized ferrites are reported and compared with values predicted by Polder's relations to validate the technique in the saturation state. To our knowledge, this is the first noniterative measurement method giving μ and κ simultaneously in a wide range of frequency.**

***Index Terms*—Anisotropic media, ferrites, microwave measurements, permeability measurement.**

I. INTRODUCTION

IN communication systems, many signal-processing functions are realized with the help of ferrimagnetic materials (ferrites) integrated in microwave devices. One important class of microwave ferrite devices is the nonreciprocal one (circulators, isolators). Another important use of ferrites is found in microwave tunable circuits (filters, resonators, switches, phase shifters). For each class of circuits, the ferrite materials are magnetized to exhibit the required properties. In practice, ferrites are magnetized by applying a dc magnetic field. Saturated or partially magnetized ferrites are anisotropic media due to the alignment of the magnetic moments in the dc field direction. Their permeability is then a tensor quantity whose components depend on intrinsic properties of the medium as saturation magnetization $4\pi M_s$, magnetocrystalline anisotropy field H_a, but also on structure properties as resonance linewidth ΔH, chemical composition, porosity, and grain size. The permeability tensor components are function of the frequency and strength of the applied dc magnetic field.

The design of a microwave device requires very accurate knowledge of the electromagnetic parameters of materials used in the different regions of the circuit. For magnetized materials, off-diagonal components of the permeability tensor have often been ignored. This is partly due to the analytic complexity of handling such expressions and the difficulty in measuring them. Although they are negligible in some materials [1], they are substantial for others, with a magnitude comparable to that of the diagonal terms. Therefore, the off-diagonal components cannot be ignored. Until now, two different approaches have been followed to predict the variations of the permeability tensor components versus the frequency and the dc magnetizing field.

The first approach consists in using theoretical or semiemperical models for the permeability tensor of ferrites. In the saturated state, all magnetic moments are aligned. Analytical expressions for the components μ and κ of the permeability tensor in a saturated ferrite were derived by Polder [2]. In a partly magnetized state, the ferrite behavior is more difficult to predict due to the complicated geometry of magnetic domains and the interactions between them. Unfortunately, the existing models [3]–[5] do not simultaneously provide all tensor components and their domain of validity is limited.

The second approach is based on the use of experimental techniques. Current methods for measuring the permeability tensor components are resonant methods [6]. However, the measurements are limited by the cavity resonator to a fixed frequency. The well-known Nicolson–Ross (NR) procedure [7] has been used to measure magnetized materials in a wide frequency range. The sample is introduced into a coaxial line and is submitted to a dc magnetic field. In this case, the NR procedure, which assumes that only a TEM mode is propagated in the line, is rather inexact. The permeability measured is a scalar quantity whose magnitude and gyromagnetic resonance frequency are not, in general, comparable to those of the permeability tensor components [8]. No information is present on the anisotropic nature of the medium.

The elaboration of new measurement methods, which provide the broad-band determination of the complex tensorial permeability of magnetized materials, is important for their practical applications. It will permit a better understanding of the wave propagation through magnetized media and a thorough prediction of the performances of microwave gyromagnetic devices.

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II. DESCRIPTION OF THE METHOD

A. Principle

Whereas the permittivity $\varepsilon = \varepsilon_0 \varepsilon_f$ is a scalar quantity in polycrystalline ferrites, the permeability $\overleftrightarrow{\mu}$ is known to have tensor properties. Assuming that the static magnetic field H_0 is in the y-direction, we have

$$\overleftrightarrow{\mu} = \mu_0 \begin{pmatrix} \mu & 0 & j\kappa \\ 0 & \mu_y & 0 \\ -j\kappa & 0 & \mu \end{pmatrix}$$

where ε_0 and μ_0 are the permittivity and permeability of vacuum, and ε_f is the relative permittivity of the ferrite. Electric and magnetic losses in the ferrite are described by regarding ε_f, μ, κ, and μ_y as complex quantities

$$\varepsilon_f = \varepsilon'_f - j\varepsilon''_f \quad \mu = \mu' - j\mu'' \quad \kappa = \kappa' - j\kappa'' \quad \mu_y = \mu'_y - j\mu''_y.$$

Thus, the microwave properties of a magnetized ferrite are completely described by eight intrinsic parameters ε'_f, ε''_f, μ', μ'', κ', κ'', μ'_y, and μ''_y.

For the reflection/transmission characterization method, the measured parameters are the scattering parameters (S-parameters) of a transmission line or a waveguide containing the test sample. The S-paramaters of the cell ($S_{11}, S_{21}, S_{12}, S_{22}$) are measured in a wide frequency range using an automatic network analyzer. If the cell is reciprocal ($S_{11} = S_{22}, S_{21} = S_{12}$) the number of independent measured parameters is insufficient to determine ε_f, μ, κ, and μ_y in a single experimental phase. At a certain fixed frequency value, three independent S-parameters are required to find the three permeability tensor components μ, κ, and μ_y. The only solution for the determination of the complex tensorial permeability of magnetized materials is then to use a nonreciprocal cell ($S_{21} \neq S_{12}$). The field displacement effect in gyromagnetic propagation structures [9] is used to provide the nonreciprocal behavior of the measurement cell.

The anisotropy of the magnetized material implies that the region where the microwave energy is concentrated in the cell is different when the direction of wave propagation is reversed. Unfortunately, the cell is reciprocal when the magnetized material entirely fills the cross section of the propagation structure in spite of the material nonreciprocity. On the contrary, when the cross section of the cell is asymmetrically loaded with the test sample, the propagation constants and field configurations of the various modes of the propagation structure are different for the two opposite directions of wave propagation.

B. Measurement Cell

The measurement cell we have manufactured is a strip transmission line composed of a rigid center conductor (strip) between the upper and lower ground planes (Fig. 1). The central zone between the strip and lower ground plane is filled with the ferrite material that is to be characterized. The center conductor is substantially wide compared with the thickness of the ferrite. In this configuration, most of the microwave energy is concentrated in the rectangular section containing the test sample, which permits to increase the cell sensitivity. To design the empty line (i.e., the line without the ferrite sample under test) for a characteristic impedance of 50 Ω, the ratio of the strip width W to the sample thickness h is equal to five. Moreover, the nonequidistance between the center conductor and ground planes enables us to have the microstrip-line configuration when the material under test is set in the cell. The field pattern of the dominant quasi-TEM mode of a microstrip line is well adapted for the measurement of magnetic plate samples [10].

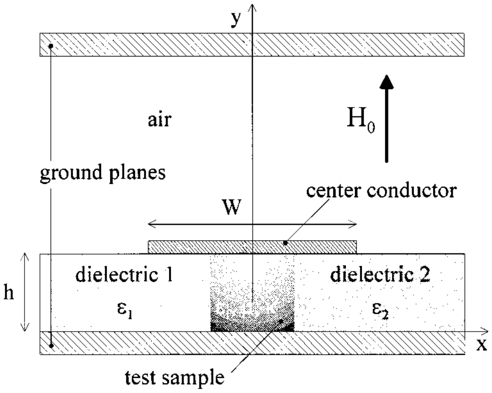

Fig. 1. Cross section of the measurement cell containing the test sample and dielectric slabs.

As previously mentioned, anisotropic properties of the magnetized material are insufficient to insure the nonreciprocal behavior of the measurement cell. Indeed, the field pattern of the dominant mode is laterally reversed for the two propagation directions implying the same phase velocities and loss for the direct and reverse waves if the cell is symmetrically loaded with the test sample. To obtain $S_{21} \neq S_{12}$, the cell must be asymmetrically loaded, e.g., by using two different dielectric media. A high-dielectric-constant slab is set under an edge of the strip and a low dielectric-constant slab is set under the other edge (Fig. 1). When the dc magnetic field H_0 is applied in the y-direction, the field displacement in the propagation structure implies that the microwave energy is concentrated on the high-dielectric side of the strip for the direct wave and the low-dielectric side of the strip for the reverse wave. In the first case, the wave is slowed due to a great value for the propagation constant of the dominant mode. In the second case, the value of the propagation constant of the quasi-TEM mode is smaller. On both sides of the (*yOz*)-plane, there is a region with a high level of microwave energy and another that is deserted. That brings about the wanted nonreciprocal behavior of the cell.

The experimental transmission response of the measurement cell containing a yttrium–iron–garnet (YIG) ferrite is given in Fig. 2 at zero dc field and when the dc field $H_0 = 1$ kOe. The dielectric constant of the ferrite is $\varepsilon_f = 14.9$. The dielectric media used to insure the nonreciprocity of the cell are the air ($\varepsilon_1 = 1$) and a titania (TiO_2) sample with a relative permittivity ε_2 of 15.5. These experimental results bringing to the fore the nonreciprocal behavior of the manufactured cell when the characterized material is magnetized prove the feasibility of the method.

III. THEORY

A. Electromagnetic Analysis

The electromagnetic analysis of the measurement cell is based on the transmission-line theory, which assumes that the

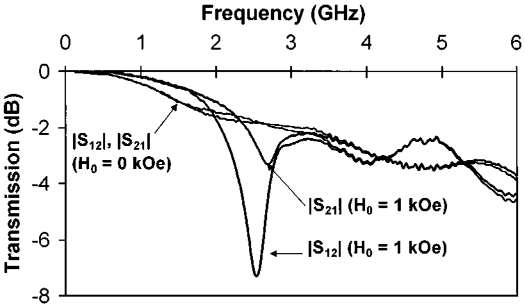

Fig. 2. Transmission response of the cell containing a YIG ferrite. Comparison of S_{12} and S_{21} magnitudes at zero dc field and when the dc field $H_0 = 1$ kOe.

dominant mode in the strip transmission line has no longitudinal field components at low frequencies. It is called the quasi-TEM mode. The transmission-line theory, which was frequently employed in the past to analyze multiconductor reciprocal transmission lines [11], has been recently applied to lines with nonreciprocal behavior [12], [13]. To take into account anisotropic properties of magnetized magnetic materials and also asymmetrical cross section of the cell, a new line parameter has been introduced in the equivalent representation of the transmission line: the characteristic memductance M [12], [13]. From that time, this new parameter can be used to model our measurement cell.

By solving Telegrapher equations including the M parameter, two solutions γ^+ and γ^- arise for the propagation constant of the nonreciprocal line. γ^+ and γ^- correspond to the forward $(+)$ and the backward $(-)$ sense of propagation, respectively [12], [13], as follows:

$$\begin{cases} \gamma^+ = \omega\left(\sqrt{M^2L^2 + LC} + ML\right) \\ \gamma^- = \omega\left(\sqrt{M^2L^2 + LC} - ML\right) \end{cases} \tag{1}$$

where ω is the signal angular frequency and L, C, and M are, respectively, the inductance per unit of length (p.u.l), the capacitance p.u.l and the characteristic memductance p.u.l of the region of the cell containing the magnetized material (Fig. 3). The expressions of L, C, and M are given by [12], [13]

$$\begin{cases} L = \dfrac{h\mu_0}{2} \dfrac{\mu(\omega)}{(b_1 - a_1) \cdot \mu(\omega) + a_1} \\ C = \dfrac{\varepsilon_0 (\varepsilon_1 + \varepsilon_2) \cdot (b_1 - a_1) + 2a_1\varepsilon_0\varepsilon_f}{h} \\ M = \dfrac{\varepsilon_0 (\varepsilon_1 - \varepsilon_2) \cdot a_1 (b_1 - a_1)}{h} \dfrac{\omega \cdot \kappa(\omega)}{\mu(\omega)} \end{cases} \tag{2}$$

where $\mu(\omega)$ and $\kappa(\omega)$ are the diagonal and off-diagonal coefficients of the permeability tensor. The μ_y component of the permeability tensor vanishes from the dispersion relations. The reason for that lies in the fact that, in the quasi-TEM assumption, no microwave magnetic-field component ever excites the μ_y component. Consequently, only the μ and κ parameters, which interfere in calculations, might be simultaneously determined using this measurement technique.

The global transfer matrix $[T]$ of the measurement cell is calculated by multiplying three transfer matrices that represent the discontinuity between empty and loaded regions, the wave propagation in the region filled with the test sample (length d), and the discontinuity between loaded and empty regions (Fig. 4), respectively. The first discontinuity is characterized by a reflection coefficient R^+ and a transmission coefficient T^+ and the second is characterized by a reflection coefficient R^- and a transmission coefficient T^-. Finally, the S-parameters of the cell are obtained thanks to relations between the transfer matrix $[T]$ and scattering matrix $[S]$

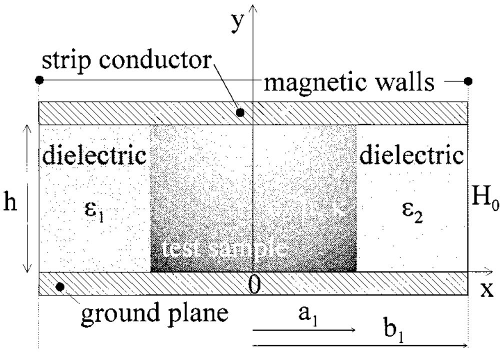

Fig. 3. Approximate equivalent of the cross section of the cell in analyzable form.

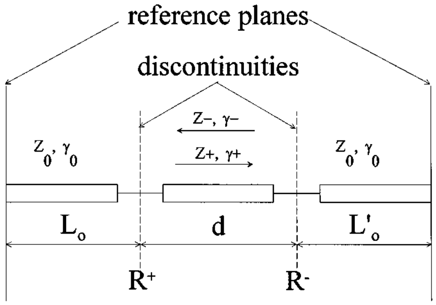

Fig. 4. Schematic diagram of the measurement cell containing the sample under test.

$$\begin{cases} S_{11} = \dfrac{R^+(1 - T^+T^-)}{1 - R^+R^-T^+T^-} & S_{12} = \dfrac{T^-(1 - R^+R^-)}{1 - R^+R^-T^+T^-} \\ S_{21} = \dfrac{T^+(1 - R^+R^-)}{1 - R^+R^-T^+T^-} & S_{22} = \dfrac{R^-(1 - T^+T^-)}{1 - R^+R^-T^+T^-} \end{cases} \tag{3}$$

with

$$\begin{aligned} R^+ &= \frac{Z^+ - Z_o}{Z^+ + Z_o} \\ R^- &= \frac{Z^- - Z_o}{Z^- + Z_o} \\ T^+ &= e^{-j\gamma^+ d} \\ T^- &= e^{-j\gamma^+ d} \end{aligned} \tag{4}$$

where Z_0 is the characteristic impedance of the empty transmission-line section ($Z_0 = 50\ \Omega$), and Z^+ and Z^- the characteristic impedances of the line containing the magnetized material for the forward $(+)$ and backward $(-)$ wave propagation

$$Z^+ = \frac{L\omega}{\gamma^+} \quad Z^- = \frac{L\omega}{\gamma^-}. \tag{5}$$

The equations shown in (3) giving the S-parameters of the nonreciprocal cell are analytical. Therefore, their computation is extremely simple and the calculation time well reduced.

The quasi-TEM assumption is experimentally well verified in the centimeter-wave range as long as the width W of the center conducting strip is sufficiently wide compared with the separation h between the strip and lower ground plane. For the manufactured cell, the W/h ratio is five ($W = 9$ mm, $h = 1.8$ mm). In this configuration, the upper limit of the validity range of the quasi-TEM approximation is 7.15 GHz [14]. The electromagnetic analysis described in this section is valid for a parallel-plate waveguide with magnetic walls (Fig. 3). Our measurement cell is composed of a strip line (Fig. 1). We have compared the theoretical values of the propagation constant given by (1) with those given by a full-wave analysis of our measurement cell based on the moments method.[1] When a dielectric material with a relative permittivity of ten is set in our cell, the relative difference between the propagation constants is of 4.54% at 6 GHz. As we will see further in this paper, this uncertainty is of the order of those caused by the experimental test device imperfections.

B. Inverse Problem

From a given geometry of the measurement cell and magnetic material, the S-parameters are calculated by using the electromagnetic analysis previously described, supposing that the permittivity and permeability of each element present in the cell are known. In this part, calculation of the complex diagonal and off-diagonal components of the permeability tensor of the magnetized material from the measured S-parameters (inverse problem) is presented. To permit the resolution of the inverse problem, without using any numerical optimization procedure, which requires important calculation times, we have established explicit relations between the unknown coefficients $\mu(\omega)$ and $\kappa(\omega)$ and the S-parameters of the test device.

The inverse problem runs in the following two steps.

Step 1) Calculation of the propagation constants (γ^+, γ^-) of the nonreciprocal region of the cell from S-parameters.

Step 2) $(\mu(\omega), \kappa(\omega))$ computation from (γ^+, γ^-).

The transmission coefficients T^+ and T^- are obtained from (3) as follows:

$$\begin{cases} T^+ = \dfrac{S_{21}}{1 - R^+ S_{22}} \\ T^- = \dfrac{S_{12}}{1 - R^+ S_{22}} \end{cases} \tag{6}$$

where R^+ and R^- are solutions of the following equations:

$$S_{22}(R^+)^2 - (S_{11}S_{22} - S_{12}S_{21} + 1)\, R^+ + S_{11} = 0$$

with

$$R^- = \frac{R^+ S_{22}}{S_{11}}. \tag{7}$$

and the right sign in the expression of R^+ is chosen so that $|R^+| \leq 1$.

The propagation constants γ^+ and γ^- are directly deduced from S-parameters of the nonreciprocal region of the cell containing the material under test by associating (4) and (6) as follows:

$$\begin{cases} \gamma^+ = \dfrac{j}{d} \cdot \ln\left(\dfrac{S_{21}}{1 - R^+ S_{22}}\right) \\ \gamma^- = \dfrac{j}{d} \cdot \ln\left(\dfrac{S_{12}}{1 - R^+ S_{22}}\right) \end{cases} \tag{8}$$

where d is the length of the sample following the z-axis of propagation (Fig. 4).

By identifying equations in (1) and (8) and also considering the relations of (2), we find the expressions of the diagonal $\mu(\omega) = \mu'(\omega) - j\mu''(\omega)$ and off-diagonal $\kappa(\omega) = \kappa'(\omega) - j\kappa''(\omega)$ components of the permeability tensor of the magnetized ferrimagnetic or magnetic composite material, which is to be characterized as follows:

$$\begin{aligned} &\mu(\omega) \\ &\quad = \frac{2a_1 \cdot \gamma^+\gamma^-}{\mu_0\varepsilon_0\omega^2\big[(b_1 - a_1)\cdot(\varepsilon_1 + \varepsilon_2) + 2a_1\varepsilon_f\big] - 2\,(b_1 - a_1)\cdot\gamma^+\gamma^-} \\ &\kappa(\omega) \\ &\quad = \frac{\big[(b_1 - a_1)\cdot\mu(\omega) + a_1\big]\cdot(\gamma^+ - \gamma^-)}{\mu_0\varepsilon_0\omega^2\,(\varepsilon_1 - \varepsilon_2)\cdot a_1\,(b_1 - a_1)}. \end{aligned} \tag{9}$$

The relations of (9) directly give coefficients μ and κ as a function of the signal angular frequency ω, the permittivity ε_0 and the permeability μ_0 of vacuum, dimensions a_1 and b_1, the relative permittivities ε_1 and ε_2 of the dielectrics 1 and 2, the relative permittivity ε_f of the magnetized magnetic material (Fig. 3) and, finally, the coefficients γ^+ and γ^- analytically deduced from S-parameters of the cell, which are measured with a network analyzer. These relations are advantageously valid for partially magnetized or saturated materials over a broad frequency band as long as the quasi-TEM approximation can be exploited.

IV. EXPERIMENTAL RESULTS

A. Test Device

The S-parameter measurements of the nonreciprocal cell are performed in the 130-MHz–6-GHz frequency band with a network analyzer system (HP 8720A) [15]. Systematic errors caused by defects of the network analyzer (coaxial cables, electronic components, ...) are reduced by performing the conventional short-open-load-through (SOLT) calibration. The impedance mismatch at the coaxial-to-stripline connection is characterized and removed by exploiting the S-parameter measurements of the cell without the material that is to be characterized.

To obtain the best possible transition from the stripline to network analyzer, the center conductor was bevelled to a point (20° with respect to the housing wall) and soldered to the center conductors of the APC-7 connectors attached outside the housing. The rectangular ferrite sample to be characterized is laid on the lower ground plane and then slid between the strip and ground plane. Its thickness is equal to the distance between the strip and lower ground plane. No laterally conductive walls are necessary because the ground-plane width ($L = 30$ mm) is wider

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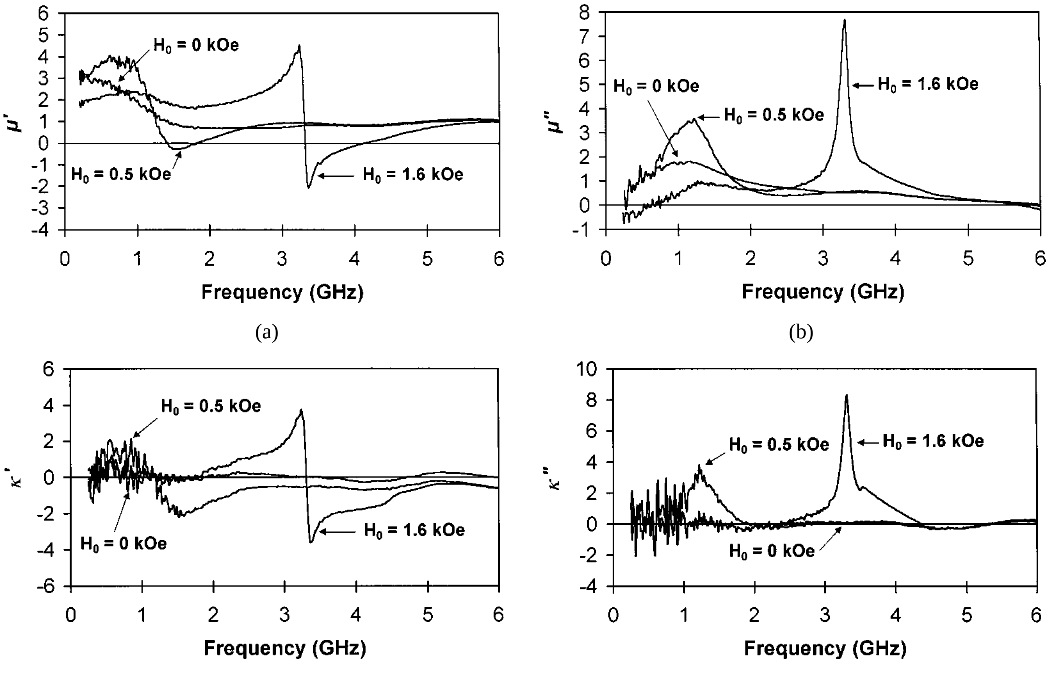
[1] HP-MDS Software, release 7.10, Hewlett-Packard Company, Santa Rosa, CA.



(a) (b)

(c) (d)

Fig. 5. Measured $\mu = \mu' - j\mu''$ and $\kappa = \kappa' - j\kappa''$ data versus frequency for a commercial YIG ferrite ($4\pi M_s = 1.2$ kG, $H_{eff} = 380$ Oe, $\Delta H = 40$ Oe, $\varepsilon_f = 14.9$) for various dc magnetic field. (a) μ'. (b) μ''. (c) κ'. (d) κ''.

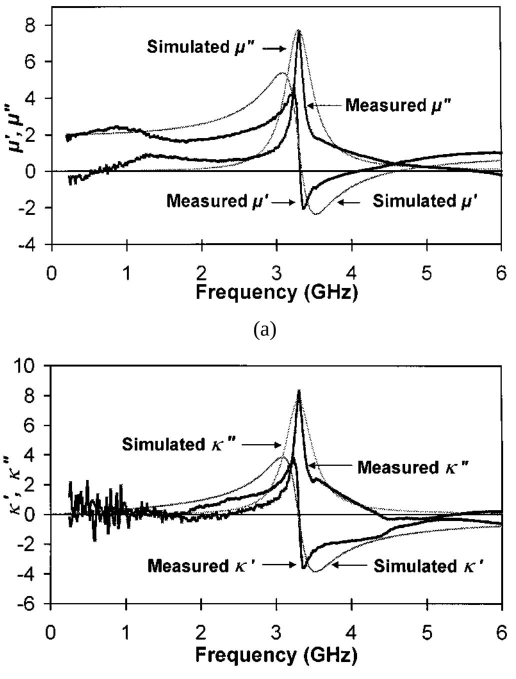
than three times the separation between the strip and the nearest ground plane (h).

The data-processing program has been implemented using a graphic programing software. It does not require any other software. It can be run with a Windows, Unix, or Macintosh operating system. It can be implemented on a usual PC. Moreover, its small size (661 kB) does not require an important part of computer memory. The input parameters of the data-processing program are the dimensions a_1, b_1, the relative permittivities ε_1, ε_2 and ε_f (Fig. 3), the cell length L, and the sample length d (Fig. 4). The output parameters μ and κ of the data-processing program are stored into a TeX format and can be processed with any usual data-processing software.

B. Results

Here, typical experimental results obtained from the measurement method we have worked out are discussed to validate (9) and to demonstrate the feasibility of the technique. Measured data versus frequency for the complex diagonal μ and off-diagonal κ components of the permeability tensor for a YIG ferrite in different magnetization states are depicted in Fig. 5. The Tekelec-Temex Society, Montreuil, France, has provided the YIG ferrite and given its magnetic and dielectric properties $-4\pi M_s = 1.2$ kG, $H_{\text{eff}} = 380$ Oe, where H_{eff} is the local effective magnetic field in the ferrite in a completely demagnetized state $\Delta H = 40$ Oe, $\varepsilon_f = 14.9$. A $5 \times 5 \times 1.8$ mm^3 rectangular piece of the YIG ferrite has been slid between the strip and ground plane of the strip transmission line. A $5 \times 10 \times 1.8$ mm^3 rectangular piece of titania is set under one edge of the strip against the YIG sample (Fig. 1). Under the other edge of the strip, the air insures the physical dissymmetry of the cell cross section. The measurement cell containing the YIG and TiO_2 samples is set in between the poles of an electromagnet in order to magnetize the ferrite under test.

We can first notice in Fig. 5 that the imaginary parts μ'' and κ'' of the permeability tensor components reveal a peak absorption of the microwave due to the damped precession of the spins around the dc magnetic-field H_0-direction. The frequency where maximal absorption occurs in loss curves is the gyromagnetic resonance frequency f_r. As can be observed in Fig. 5(b) and (d), f_r shifts with the dc magnetic field H_0 strength. A typical behavior of unsaturated materials can be observed in Fig. 5(b) and (d), where loss curves μ'' and κ'' are sharper as H_0 increases. Moreover the requirement of a nonnegative energy loss in the ferrite material imposes the restriction that μ'' and κ'' are positive. This condition is confirmed by the measured loss curves all over the exploited frequency band, as seen in Fig. 5(b) and (d). We can notice that, at zero field, the real and imaginary parts of the off-diagonal component are zero. As would be expected in any magnetization states, the real and imaginary parts of the diagonal and off-diagonal components tend toward vacuum magnetic properties ($\mu' = 1$, $\mu'' = 0$, $\kappa' = 0$, $\kappa'' = 0$) in high frequencies. We have studied the influence of the ferrite sample width on the domain of validity of the quasi-TEM approximation. We have found that the use of a ferrite sample having a smaller width increases the upper limit of the range of validity of the measured μ and κ data. For example, the requirement of a nonnegative energy loss in the test material ($\mu'' > 0$) is verified up to 5.06 GHz when using a 7-mm-width YIG sample, whereas when using a 5–mm-width YIG sample, it is verified up to 6.02 GHz [see Fig. 5(b)]. The purpose of this paper is not to present the error analysis of the measurement technique we have worked out. This study will be given in a future paper. We plan to make a rigorous electromagnetic analysis of the cell discontinuities to detect the first higher order modes and to determine



(a)

(b)

Fig. 6. Comparison between the measured μ and κ data and those given by Polder's model for the YIG ferrite for a dc magnetic field $H_0 = 1.6$ kOe. (a) μ. (b) κ.

the upper limit of the domain of validity of the quasi-TEM assumption.

In order to validate the data-processing program, theoretical and experimental values of the permeability tensor components are compared in a well-known borderline case. Indeed, when the YIG ferrite is next to saturation, measured μ and κ data can be compared with calculated data given by Polder's model [2], which is assumed to apply only to saturated media. In Fig. 6, a good agreement between theoretical and experimental values of the real and imaginary parts of μ and κ is observed over the whole exploited frequency band. At 200 MHz, the real part measured of the static permeability is of 1.97 when $H_0 = 1.6$ kOe, whereas its calculated value is of 2.02. In this case, the relative uncertainty is of 2.5%. We can also notice in Fig. 6 that the loss curves measured μ'' and κ'' are sharper than the calculated ones. The reason for that lies in the fact that the damping factor, which is an input parameter of Polder's relations, is assumed to be constant over the whole frequency range, whereas it should be calculated for each frequency value from the resonant linewidth of the ferrite ΔH given by the sample supplier.

V. DISCUSSION

The method we have worked out shows numerous advantages compared to existing characterization methods used to measure magnetized materials.

The first advantage of the method is the broadness of the exploited frequency band. The experimental results depicted in Figs. 5 and 6 are performed in the 130-MHz–6-GHz frequency range using an HP 8720 network analyzer setup. Measured μ and κ spectrum covers nearly two decades. The method can be extended to lower frequency ranges using the same data-processing program, the same measurement cell, and a network analyzer with lower operating frequencies. For example, the use of an HP 8753 network analyzer has enabled us to extend the method to 50 MHz. Cavity resonator methods can be used to measure the permeability tensor components of magnetized materials. The experimental results performed with this technique are obtained at one frequency value fixed by the cavity dimensions. The first broad-band characterization method for magnetized materials has been conceived in our laboratory. The technique is based on the reflection/transmission measurement of an X-band rectangular waveguide partly filled with the ferrite to be characterized [16], [17]. The exploited frequency band is 7–13 GHz, i.e., less than one decade. The measured μ and κ data provided by the waveguide cell and those given by the strip-line cell cannot be compared because the exploited frequency bands are different.

The second advantage of the method lies in the easiness of the computation procedure. The data-processing program can be run on a PC using an usual data-processing software. We have used a software based on graphic programing. The typical CPU time for 801 frequency points is less than 10 s using a PC with an Intel II 350-MHz processor. In comparison, the characterization method using a rectangular waveguide requires a CPU time of 20 min for 801 frequency points using an IBM RS 6000 PC [17].

The third advantage of the method lies in the easiness of the experimental procedure. The sample that is to be characterized has a rectangular shape and is slid in the cell between the strip conductor and lower ground plane. Its thickness is equal to the distance between the strip and ground plane, its width is lower than the strip conductor width and its length (dimension in the wave propagation direction) is of a few millimeters. Sample dimensions are measured with a micrometer (accuracy $= 1$ μm) and are input parameters for the data-processing program. The unique constraint for the machining of the sample affects its thickness ($t = 1.8$ mm). In order to insure the nonreciprocity of the measurement cell, a dielectric slab is set against the sample under test, as depicted in Fig. 1. Under the other edge of the strip conductor, the air plays the role of a second dielectric material. The dielectric slab has the same thickness as the test sample and can extend beyond the strip (Fig. 1).

VI. CONCLUSION

As far as we know, the measurement technique we have worked out is original. It is the first noniterative characterization method enabling the broad-band determination of the permeability tensor components of magnetized materials in a single experimental phase. The method is valid whatever the magnetization state of the material.

Analytical expressions for the complex diagonal μ and off-diagonal κ components of the permeability tensor are given as functions of the sample dimensions, cell dimensions, and S-parameters of the device. The data-processing program can be easily implemented and run using a PC. The experimental procedure is simple and does not require many machining constraints for the test sample. Unlike alternative techniques, it provides a measurement method that is simultaneously very quick, simple, cheap, and broad-band. The measurement method has been validated in a borderline case comparing in the 130-MHz–6-GHz frequency range experimental results obtained for a saturated YIG ferrite with the theoretical ones given by Polder's relations.

In a future paper, in order to extend the method to higher frequency ranges, we will study the domain of validity of the theory used for the electromagnetic analysis of the cell by comparing it to a full-wave analysis. Experimental results obtained for ferrites and composite magnetic materials in a partly magnetized state will be compared to the results given by a theoretical model of the permeability tensor developed in our laboratory.

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