Generalized Measurement Method for the Determination of the Dynamic Behavior of Magnetic Materials in Any Magnetization State

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A broad-band characterization method based on the junction of the full-wave analysis of a nonreciprocal strip transmission line with a predictive permeability tensor model is presented. The aim of this method is the direct measurement of the permeability tensor components spectra of magnetized thick samples, whatever their magnetization state is. The propagation constants of the dominant transverse electromagnetic (TEM) and higher order modes inside the measurement cell are obtained along with its scattering parameters (S-parameters). The apparition of magnetostatic modes and the nonreciprocal nature of the structure are probed. Procedures based on the use of this method to find accurate values of gyromagnetic resonance and the resonance line width (ΔH) are proposed. The direct analysis is validated by comparison of the calculated S-parameters with those obtained with an electromagnetic field simulator based on finite element methods (FEM).

Index Terms—Magnetic resonance, magnetic variables measurement, nonreciprocal wave propagation, permeability, scattering parameters.

I. INTRODUCTION

FERRITE materials are widely used for microwave applications; their good insulating behavior in high frequencies and their static magnetic field-dependent permeability make them suitable for several signal processing functions. On one side, some reciprocal devices (tunable filters, commutators and phase shifters) are based on the variation of the microwave response of ferrites under the action of a static magnetic field. On the other side, nonreciprocal devices like isolators and circulators exploit the magnetic field-induced anisotropy of ferrites. Fig. 1 shows the different magnetization states (M) found in some of the microwave devices mentioned.

The dynamic behavior of magnetized ferrites must be represented by a tensorial quantity: the permeability tensor (1)

$$\overleftrightarrow{\mu}(f,H) = \begin{pmatrix} \mu(f,H) & 0 & -j\kappa(f,H) \\ 0 & \mu_y(f,H) & 0 \\ j\kappa(f,H) & 0 & \mu(f,H) \end{pmatrix} \quad (1)$$

where μ, μ_y and κ are complex values, f is the frequency and H is the static magnetic field strength.

In order to assist the design of this type of devices, the permeability of magnetized magnetic materials must be fully characterized; that is why the need to develop a characterization method enabling the determination of the dynamic behavior of magnetized materials, whatever its magnetization state is.

II. PREVIOUS WORKS

Currently there are different methods to characterize microwave magnetic materials. For the case of demagnetized
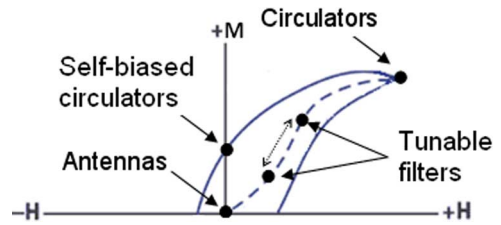
Fig. 1. Magnetization states (M) for different microwave applications.

materials transmission line-based methods are widely used [1]. For a magnetized sample, whose permeability is a tensor quantity, these methods give the effective scalar permeability

$$\mu_{eff} = \frac{\mu^2 - \kappa^2}{\mu} \quad (2)$$

where μ and κ are the diagonal and off-diagonal components of the permeability tensor (1). This effective value (2) does not show neither the same magnitude nor the same gyromagnetic resonance frequency of the tensor components μ and κ in (1).

For the case of saturated materials the cavity resonators are used [2]. These methods give the resonance line width ΔH (normally at 9.4 GHz) to characterize the losses of ferrites. Measurements of this parameter at high or low frequencies are impractical due to the cavities size constraints. Moreover, they are related to Polder's formulations [3] of the permeability tensor components which are only valid for an infinite saturated medium. In practice ferrites are not always used in a saturated state (tunable filters, self-biased circulators, etc.), even in conventional circulators where non saturated regions appear in the ferrite puck as demonstrated in [4].

In such a context a broad-band characterization method has been developed in our laboratory [5]. This method is based on the use of a microstrip coupled with a generalized quasi-transverse electromagnetic (quasi-TEM) approach. Its domain of validity is limited from the theoretical point of view by the quasi-TEM approximation to 3 GHz. From the experimental
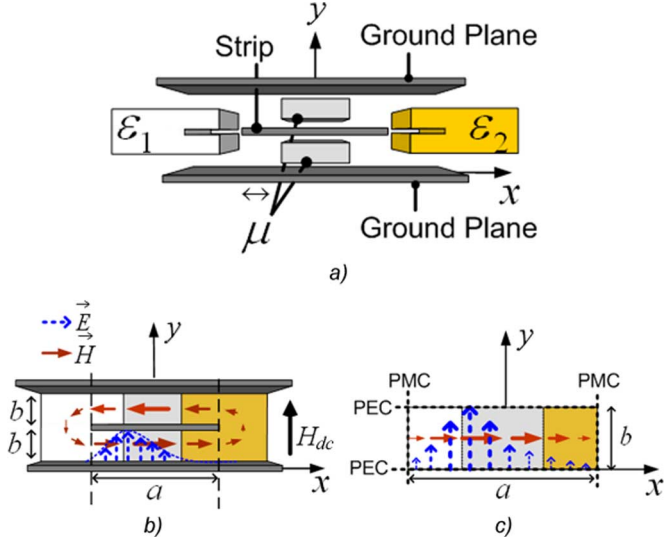
Fig. 2. a) Measurement cell. b) Field displacement for forward propagation. c) Theoretical equivalent structure.

point of view, the limitations arise from the S-parameters dimensional resonances which are related to the physical length of the sample. At these resonance frequencies, the uncertainties on the measured data increase (low values of the measured signal) making unusable the S-parameters information.

Instead, we propose an electromagnetic (EM) characterization method, in which a full-wave analysis of a measurement cell is done (mode matching method). This method should enable us to determine in a broad frequency range the permeability tensor components taking into account the magnetic DC bias. It should also give the ΔH at low and high frequencies and the real (not effective or equivalent) gyromagnetic resonance frequency of the sample.

III. DESCRIPTION OF THE MEASUREMENT METHOD

In this section the theoretical foundations of the method are shown. As a result of this procedure, the simulated S-parameters of the structure are obtained.

A. Measurement Cell

This new method is based on the use of the strip transmission line shown in Fig. 2(a). A section of the line is filled at the sides with dielectric materials showing different permittivity values and in the central region with two identical samples of magnetic material. The rest of the line is unfilled.

In this configuration the magnetized magnetic material inside the line produces a field displacement for both, forward and reverse propagation. Fig. 2(b) shows the field displacement for the forward propagation; in the reverse propagation, displacement occurs to the opposite side of the strip (E field moves to the ferrite/ε_2 interface). This displacement combined with the fact that for each direction of propagation the wave interacts mostly with a different dielectric slab yields to the nonreciprocal behavior of the line ($S_{21} \neq S_{12}$). This behavior is indispensable to get enough measured information for the computation of the tensor components, i.e., the same number of variables (complex ε, μ, κ) that measured data available (complex S_{11}, S_{21}, S_{12}).

In this structure the dominant polarization mode is purely TEM, which is an advantage over most common used lines (microstrip, coplanar) where the dominant mode is Quasi-TEM. To describe a Quasi-TEM mode in full-wave analysis, compensating factors have to be used. Adversely, the description of a TEM mode comes directly from the classical definitions of electromagnetic fields.

This structure has the strip width a greater than the height between the ground planes and the strip b (Fig. 2(b)). This is done to avoid the fringing field effects (*edge effects*) at both sides of the strip [6]. With these conditions in mind it is assumed that the energy is confined between the ground planes and the strip. This is represented by the theoretical equivalent structure shown in Fig. 2(c). Here, boundary conditions are added to close the energy inside. Perfect electric conductors (PEC) are added to represent the ground planes and the strip. Perfect magnetic conductors (PMC) are added in accordance to the EM field pattern to close the energy inside the structure. This structure represents only the bottom half of the stripline because in the other half all field are mirror quantities with inverted phase.

B. Direct Analysis

The full-wave analysis begins with the definition of the EM fields inside each material of the structure. For the description of the permeability tensor components that appear in the field definitions the General Permeability Tensor Model (GPT) [7] is introduced. This model has as input parameters the physical characteristics of the magnetic material ($4\pi Ms$ (saturation magnetization), α (damping factor), H_a (anisotropy field), N_y (shape factor), H_{dc} (DC magnetic field applied)). The GPT model describes the dynamic behavior of the permeability tensor components taking into account its magnetization state.

Then, continuity conditions are forced in both dielectric\ferrite discontinuities to form a 4 × 4 complex variable system of equations. A comparable analysis is given for a rectangular waveguide in [8]. From this system of equations, the propagation constants ($\gamma = \beta - j\alpha$) of the first n desired modes ($n/2$ forward and $n/2$ reverse) inside the line are determined. This is done using a numerical procedure developed by us that combines the dichotomic method extended to the complex plane and the Müller's method of complex root search. As a result of this procedure, Fig. 3 shows the phase constants for the first 8 modes (4 forward and 4 reverse) for a saturated ferrite.

In this figure the nonreciprocal behavior of the structure ($\beta_{\text{forward}} \neq \beta_{\text{reverse}}$) is demonstrated. Likewise, this result shows that at low frequencies the higher order modes propagate the energy in the form of magnetostatic modes (characterized at some frequencies by the low group velocities). In these conditions the higher order modes, which are normally evanescent for classic lines, become propagated modes in a nonreciprocal line. These modes can even overpass in terms of energy the TEM mode (TEM mode is typically the dominant mode in this type of transmission line). These results manifest the importance of taking into account the first significant modes with a full-wave analysis.

To obtain the scattering parameters (S-parameters) of the line, a mode matching technique for the first n excited modes at both air/materials discontinuities of the line (in the z direction) is
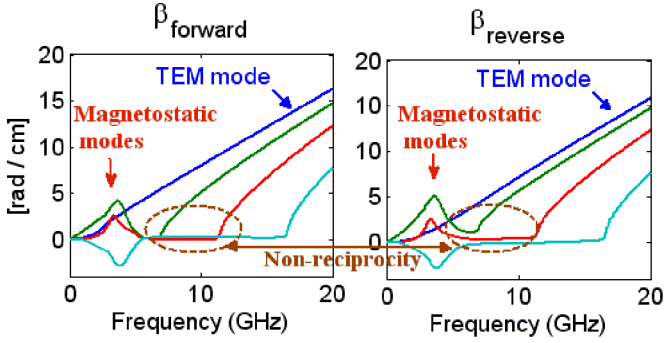
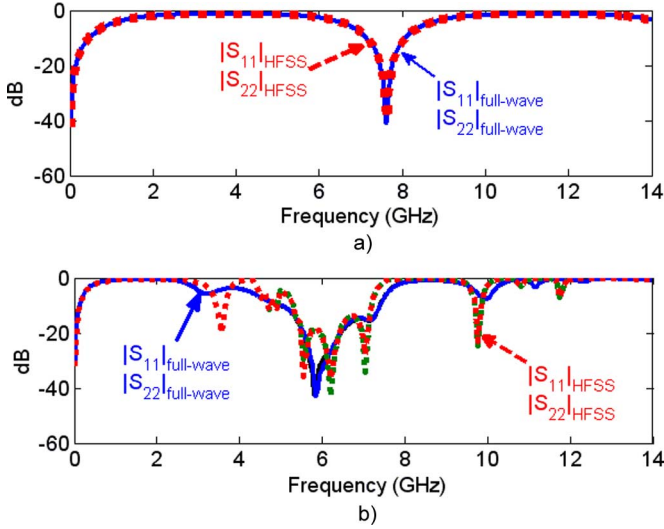Fig. 3. Reverse and forward propagation constants inside the loaded section of the line in the saturated state.

Fig. 4. Comparison of the reflection S-parameters calculated from 2 theoretical approaches (full-wave analysis and HFSS simulation). a) $\varepsilon_1 = \varepsilon_f = \varepsilon_2 = 15$. b) $\varepsilon_1 = 1.07$ (foam), $\varepsilon_2 = 15.5$ (TiO) and Y-al polycrystalline ferrite ($4\pi Ms = 1200$ G, $Ha, = 380$ Oe, $\varepsilon = 14.9$, $\tan(\gamma) < 2 \cdot 10^{-4}$, $H\,dc = 2$ KOe).

done. This results in a $2n \times 2n$ system of equations, in which the variables are the coupling reflection and transmission constants. Using the orthogonality property of modes [9], this system is solved, giving the simulated S-parameters of the measurement cell. The value of n is set to assure the convergence of the calculated S-parameters.

C. Validation of the Direct Analysis

As it is very difficult to have a ferrite with a well-known permeability spectra, comparisons at limit cases between our full-wave method and HFSS software [10] were made for the validation of the analysis. Fig. 4(a) shows the comparison of a dielectric case. A perfect agreement is obtained.

Fig. 4(b) shows the comparison of a ferrite in saturation. A good agreement between the two curves from 0 up to 14 GHz is seen. This limit in frequency is due to the apparition of the first transverse electric (TE) propagated mode at 16 GHz. In the developed analysis only one incident mode (dominant TEM mode) is assumed to be propagated in the air sections of the cell (valid from 0–16 GHz). If more bandwidth is required, the propagated superior modes in the air segment of the line could be inserted in the analysis.

D. Inverse Problem

To obtain the measured permeability tensor components (μ, μ_y, κ) a numerical optimization procedure will be developed. This procedure will match the theoretical (direct problem) and measured S-parameters of the measurement cell. The optimization will be based on a wideband error function of the form (3). In this function, only the magnitudes of the S-parameters are used to avoid phase related errors. The optimization variables of this procedure will be the GPT tensor model input data $(4\pi Ms, H_a, \alpha, N_y)$ which are directly related to the theoretical S-parameters by the full-wave analysis.

$$E = \sum_{f=f_{\min}}^{f_{\max}} \left(\sum_{i=1}^{2} \sum_{j=1}^{2} \left(\left| S_{ij\ theoretical}^{f} \right| - \left| S_{ij\ measured}^{f} \right| \right)^2 \right). \tag{3}$$

As a result of this procedure, the optimized values are used in the GPT tensor model to obtain the measured permeability spectra of the tensor components.

IV. APPLICATIONS OF THE METHOD

This characterization method will allow not only to have the wide-band response of the material properties (permeability spectra), but it would also give us the possibility to determine commonly used parameters that characterized the magnetic materials at microwave frequencies.

A. ΔH at Different Frequencies

The most known classical procedures for the determination of the magnetic loss parameter ΔH are the resonant cavity methods [2]. In these methods different resonant cavities are needed to determine ΔH at different frequencies (mono-frequency measurements). The characterization method proposed enables us to determine ΔH at different frequencies using the same measurement structure and the same magnetic sample. The main advantage of this approach is the possibility to determine ΔH at low frequencies where classical resonant methods suffer from the use of voluminous cavities and samples.

For the determination of ΔH, first the magnetic flux in the structure has to be closed to minimize demagnetizing fields. This is done by changing the metallic grounds and the strip with ferromagnetic material and closing the magnetic circuit with an electromagnet as shown in Fig. 5.

In this configuration the internal field in the magnetic material (H_{int}) will be very similar to the known bias field (H_{dc}) applied by the electromagnet. Then, the characterization method is used to find the permittivity spectra (μ' and μ'') for different bias strengths (H_{dc}).

This procedure is illustrated in Fig. 6 using calculated permeability spectra obtained from the GPT model [7]. The permeability spectra $\mu''(f)$ are stored for different DC field strengths (Fig. 6(a)). Then, the $\mu''(H)$ curve is deduced for a fixed frequency (fo) from the data stored (Fig. 6(b)). The combination of this procedure with the characterization method developed
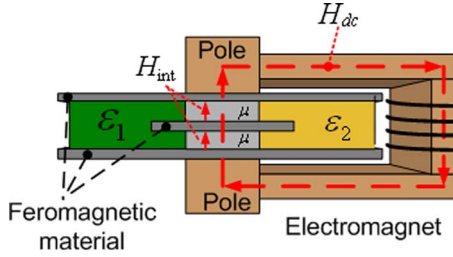
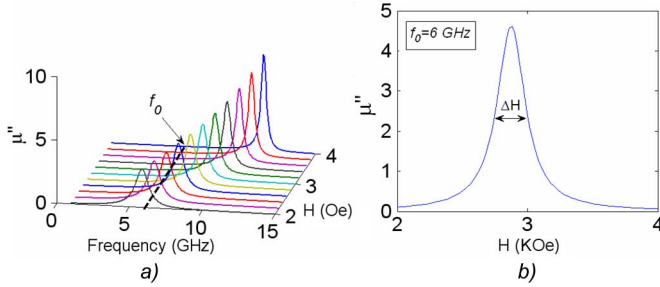Fig. 5. Schematic circuit for minimization of demagnetization fields.

Fig. 6. a) μ'' simulated from the GPT model within a frequency range from 0–15 GHz and a Hdc range from 2–4 KOe. The material characteristics are $4\pi\mathrm{M} = 1200\,\mathrm{s}$, $Ha = 40$, $\Delta H = 40\,\mathrm{Oe}$. b) ΔH obtained at $f_0 = 6\,\mathrm{GHz}$.

Fig. 7. Gyromagnetic resonance vs. absorption peak of a polycrystalline ferrite ($4\pi Ms = 1200\,\mathrm{G}$, $Ha, = 380\,\mathrm{Oe}$, $\varepsilon = 14.9$, $\tan(\gamma) < 2 \cdot 10^{-4}$, $Hdc = 2\,\mathrm{KOe}$). $\varepsilon_1 = 1.07 - \mathrm{j}0.01$ (foam) and $\varepsilon_2 = 15.5 - \mathrm{j}0.01$ (TiO).

will allow to measure the ΔH within a broad range of frequencies pending on the saturation of the ferrite samples.

B. Real Gyromagnetic Resonance

Fig. 7 shows the response for the permeability tensor component μ and the corresponding transmission parameters obtained from the direct analysis.

From this figure it is quite easily inferred that the frequency of minimal transmission through the line (f_a) and the gyromagnetic resonance frequency of the ferrite (f_m) are different. This can be explained by the non-homogeneous character of the cross section of the line. The S-parameters are directly dependent on the effective permeability of the line which exhibits an absorption peak at f_a. But, the relation between the latter permeability and that of the ferrite sample is complex (not straight forward); this explains the difference between the resonance frequencies of the respective permeabilities $(f_a \neq f_{\mathrm{m}})$. Analytical forms of this relation can be found from mixing rules using the Quasi-static approximation. Our EM analysis provides an accurate relation based on the resolution of the Maxwell's equations.

FMR measurement techniques based on the use of non-homogeneous propagation structures [11] assume that these two frequencies are the same to find the anisotropy field of magnetic materials. With the method proposed, it is possible to measure the real gyromagnetic resonance of the ferrite and therefore obtain accurate values for the anisotropy field, gyromagnetic ratio or Landé g-factor.

V. CONCLUSION

The broadband characterization method proposed overcomes some of the drawbacks of previous methods to determine the RF permeability of ferrites such as bandwidth and S-parameters dimensional resonance related errors. It also gives a realistic approach of the gyromagnetic resonance in ferrite-loaded circuits. From this method experimental procedures could be easily developed to accurately determine magnetic material parameters such as the resonance line width (ΔH), gyromagnetic resonance frequency (FMR), anisotropy field or Landé g-factor. This method could cover also the needs of new growing technologies in which the character "in situ" of the measured magnetic properties is primordial i.e., LTCC technology where ferrite, dielectric and metallic layers are co-fired at the same time.

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