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ON THE DETERMINATION OF THE PERMEABILITY TENSOR OF MAGNETIZED MATERIALS. APPLICATION TO THE DESIGN OF NONRECIPROCAL AND TUNABLE MICROWAVE DEVICES

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Abstract: - In this paper, the main microwave applications of magnetized materials are briefly recalled. The theories developed to predict their dynamic behavior are presented. Then the measurement methods that enable us to compare the theoretical results with experimental data are described. Propects about the needs in new microwave magnetic structures for future applications are finally discussed. We focus these prospects on millimeter self-biased circulators using hexaferrites set in a remanent state. These considerations highlight the need for thorough investigations targeted to the design of magnetized material-based microwave devices to take into account, at the same time, the dc field non-uniformity, the unsaturated state of certain regions of the magnetized substrate and realistic values for the permeability tensor components.

Key words: Permeability, ferrites, microwave measurements, magnetic microwave devices.

I. Introduction

THE electromagnetic properties of magnetized materials (polycristalline ferrites, magneto-dielectric composites) are required to realize two important classes of microwave devices: nonreciprocal (circulators and isolators) and tunable (filters, resonators, switches, phase-shifters, etc.) circuits. The first class is based on the field-induced anisotropy of ferrites and the second one on their dc field-dependent permeability.

In practice, the nonreciprocity or the tunability of the device is obtained by applying an external dc magnetic field (fixed or variable in strength) on the magnetic sample integrated in the circuit. Magnetized materials are anisotropic media due to the alignment of the magnetic moments in the dc field direction. Thus, their permeability is a tensor quantity and the design of a magnetic microwave device requires very accurate knowledge of this tensor. Assuming that a dc magnetic field is applied along the z-direction, the permeability tensor is:

$$\vec{\mu} = \mu_0 \begin{pmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_z \end{pmatrix}$$

where μ_0 is the permittivity of vacuum and μ, κ and μ_z are complex quantities.

The off-diagonal components κ of the permeability tensor have often been ignored in the literature. 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 (thin layers with in-plane anisotropy), they can be large for others, with a magnitude of the same order than the diagonal terms. Moreover, for nonreciprocal devices where the magnetic material is assumed to be saturated by permanent magnets, studies have demonstrated the unsaturated character of regions in the ferrite puck due to the nonuniformity of the demagnetized fields and of the DC bias field [1], [2]. In that case, the analytical expressions commonly used to compute the frequency and dc-field dependences of the permeability tensor components of saturated media (Polder formulations [3]) are not valid anymore.

II. Permeability tensor models

The dynamic response (permeability) of a polycrystalline ferrite excited by an electromagnetic wave is very different depending on its magnetization state. According to the applied dc field strength, a material can be demagnetized (zero or coercitive field), partially magnetized (moderate field or zero field at the remanent state) or saturated (high field).

In the saturated state, all the magnetic moments in the ferrite are aligned along the applied dc field direction. The diagonal and off-diagonal component spectra of the permeability tensor exhibit a resonant behavior. This resonance, due to the gyroscopic precession of the magnetic moments around the applied dc field direction, takes place at a well-defined frequency proportional to the dc field strength. The absorption peak which appears on the spectra of the imaginary parts of the permeability tensor components is relatively narrow, and its shape is well described by the Polder formulations [3].

In a demagnetized or partially magnetized state, the absorption peak observed in experiment is much broader. Among the physical phenomena which lead to this low-field loss region, one of the most important, described by Polder and Smit [4], has a maximal effect when magnetic domains with opposite magnetization directions are present in the material. That results in the spreading of the resonance frequencies and generates magnetic losses in a frequency band from the frequency $\omega_a=\gamma H_k$, proportional to the anisotropy field, up to a frequency $\omega_m=\gamma M_s$, proportional to the saturation magnetization of the medium (γ is the gyromagnetic ratio).

The permeability of ferrite in a partially magnetized state has been treated by many authors [5-9]. But no theory quantified the Polder-Smit effect. Moreover, in the theoretical approaches proposed only the ratio M/M_s (M is the magnetization of the material) characterizes the magnetization state of the ferrite, which is not sufficient to accurately describe its static magnetic properties (internal dc field, domain configuration, moment directions,...). Therefore these models cannot be used to thoroughly determine the permeability, especially for hard materials which exhibit a rectangular hysteresis loop such as Barium hexaferrites. In addition, for models [6] and [9], the domain configuration is too idealized to represent realistic situations.

The fundamental principle of the model developed by Gelin *et al*. [10, 11, 14] consists in modifying the well-known Landau - Lifchitz – Gilbert (LLG) equation to take into account the demagnetizing effects relating to both grain and domain shapes in accordance with the Polder - Smit and Smit - Wijn's theories [4, 12], which describe the material response in the low-field loss region. The motion of the magnetization vectors $\vec{M}_1$ and $\vec{M}_2$ relating to two interacting adjacent domains in a grain (crystallite), itself surrounded by other grains, under the action of a rf magnetic field *h* is described by the following system of coupled equations:

$$
\begin{aligned}
\frac{d\vec{M}_1}{dt} &= -\gamma\vec{M}_1 \wedge \left(\vec{H}_1 + \vec{h} - \vec{h}_d - \vec{h}_g\right) + \frac{\alpha}{Ms}\vec{M}_1 \wedge \frac{d\vec{M}_1}{dt} \\
\frac{d\vec{M}_2}{dt} &= -\gamma\vec{M}_2 \wedge \left(\vec{H}_2 + \vec{h} + \vec{h}_d - \vec{h}_g\right) + \frac{\alpha}{Ms}\vec{M}_2 \wedge \frac{d\vec{M}_2}{dt}
\end{aligned} \quad (1)
$$

where the quantity $\vec{h}_d = n_d\left(\vec{m}_1 - \vec{m}_2\right)$ represents the dynamic demagnetizing field due to the shape of domain 1 including the Polder-Smit effect which couples the motion of the rf magnetization vectors of adjacent domains, n_d is the demagnetizing coefficient related to the domain shapes and α is the damping factor. The quantity

$$\vec{h}_g = n_g(\vec{m}_1 + \vec{m}_2 - \frac{M}{Ms} < \vec{m} >)$$

is the dynamic demagnetizing field due to the grain immersed in an effective medium characterized by a mean rf magnetization $<\vec{m}>$ and n_g is the demagnetizing coefficient related to the grain shapes.

Knowing all terms of the LLG equation in domain *i*, solving (1) gives the relation $\vec{m}_i = \tilde{\chi}_i \vec{h}$, where $\tilde{\chi}_i$ is the local susceptibility tensor. The last stage consists in summing from a statistical approach all the local dynamic magnetizations $\vec{m}_i$ over all directions to determine the effective permeability tensor of the material. For this integral calculation, distribution functions of the demagnetizing coefficient are used to take the diversity of domain and grain shapes into account. Theoretical results obtained for demagnetized ferrites can be found in [11].

To enforce the predictive character of the calculation, the generalized permeability tensor model we propose (GPT model) has been formulated in terms of the external dc magnetic field H_0 instead of the magnetization state M/M_s, as it was done in existing models. Then, it is necessary to determine the internal static quantities in each domain of the material as a function of the applied field, including effects associated with hysteresis, the shape of the macroscopic sample, the texture of the material (preferential orientation or not), *etc*. To do so hysteresis models of magnetization (see for example the Stoner and Wohlfarth model [13]) must be used to provide these internal static quantities. From these additional data, a generalized permeability tensor (GPT) model has been developed [14]. For polycrystalline ferrites containing randomly oriented grains, this model gives results in good accordance with experiments. In particular, it predicts a spreading of gyromagnetic resonance frequencies as well as a behavior of the permeability imaginary part spectrum μ" comparable to that experimentally observed for frequencies below $\omega_m=\gamma Ms$. For saturated media, our results match with those given by Polder formulations.

III. Measurement methods

Current methods for measuring the permeability tensor components were cavity resonant methods [15]. But the measurements were limited to a fixed frequency by the cavity dimensions and were less accurate in the vicinity of the gyromagnetic resonance (decreasing of the quality factor of the cavity). The well-known Nicolson-Ross (NR) procedure [16] 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 longitudinal dc magnetic field. In that case, the NR procedure which assumes that only a transverse electromagnetic (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. As the cell is reciprocal no information on the anisotropic nature of the medium can be obtained.

The key element for the design of a measurement cell adapted to the broad band characterization of magnetized materials is to insure its nonreciprocal character to have the same number of measurable scattering parameters (S-parameters, with $S_{21} \neq S_{12}$) as for the material parameters we want to determine (complex permittivity and complex permeability tensor components).

While basing our cell design on this fundamental principle, we have worked out three techniques based on the field displacement effect in propagation structures due to the anisotropy of the magnetized material. This effect leads to the nonreciprocity of the measurement cells.

The first technique uses a rectangular waveguide partly filled with the sample under test. The electromagnetic full-wave analysis of the cell is based on the mode matching method which permits to take into account higher order modes such as magnetostatic modes [17]. The resolution of the inverse problem has required the use of a numerical optimization procedure based of the Raphson-Newton method. The S-parameters are measured by a network analyzer in the *X*-band and the cell is set between the poles of an electromagnet in order to magnetize the sample under test [18]. But the important calculation time required for this technique (20 min for 801 frequency points) due to its iterative process encouraged us to design a new measurement method.

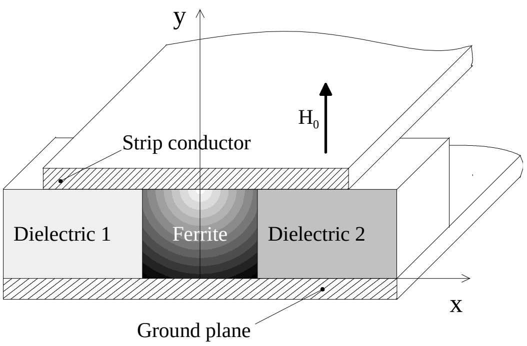

Fig. 1. Nonreciprocal microstrip measurement cell.

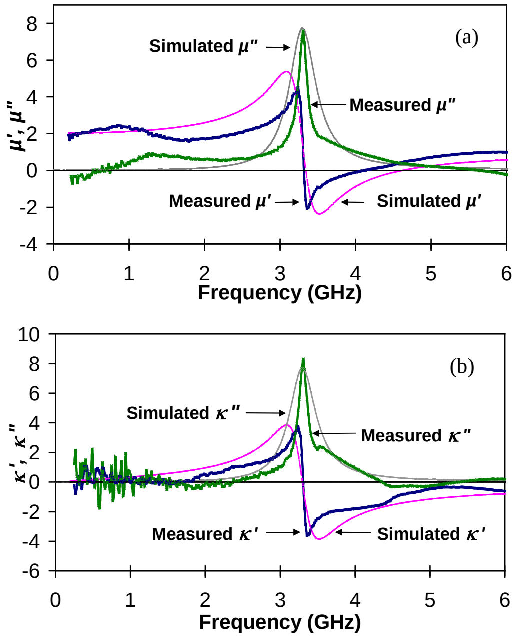

Fig. 2. Theory/experiment comparison for the permeability tensor components of a saturated YIG ferrite. . a. Real and imaginary parts of the diagonal component. b. Real and imaginary parts of the off-diagonal component.

The second measurement cell we worked out is composed of a nonreciprocal microstrip transmission-line partly filled with the sample which is to be characterized. The cell is asymmetrically loaded by using a high and a low dielectric-constant slabs set on each side of the sample under test in order to insure the nonreciprocity of the cell (Fig. 1). The data processing program is based on a generalized quasi-TEM approximation for nonreciprocal propagation structures [19]. From this theory, we have established analytical relations to compute the complex scalar permittivity and permeability tensor components of the sample under test from the measured S-parameters [20]. The S-parameters of the cell are measured in a wide frequency range (30 kHz – 6 GHz) using a network analyzer setup.

To our knowledge, this method is the first non iterative measurement method giving simultaneously the diagonal and off-diagonal components of the permeability tensor in a single experimental phase and in a wide range of frequencies, as it can be done for isotropic materials (complex scalar permittivity and permeability) by Weir's technique [21]. To illustrate the experimental results obtained from this technique, Fig. 2 shows a comparison for a satured YIG ferrite between measured data and calculated values obtained from Polder formulations [3].

This method was recently improved to broaden the exploited frequency range (0.5-13 GHz). The new measurement cell is now a strip transmission-line and the data processing program is based on a fullwave EM analysis [22].

IV. Application to the design of circulators

One among the major parameter that strongly affects the performances of circulators is the dc-bias field. Some studies have shown a reduction of the *Y*-junction circulator transmission band induced by the non-uniformity of the dc bias-field created, within the ferrite slab, by permanent magnet [2]. In practice, this non-uniformity is quite frequent because the shape of the ferrite sample is rarely an ellipsoid and the size of the polarization circuit has to be strongly reduced for miniaturization purpose. The increasing needs for miniature planar microwave circuits have encouraged designers to employ microstrip technology because of available solutions liable to enhance circulators compactness. The objective would be to polarize the device with only one magnet, or even without magnet using self-biased ferrites (hexaferrites with preferential orientation of the magnetic moments). However, compared to the stripline structure these solutions enhance the nonuniformity of the magnetic dc-bias field, but at the expense of device performances.

Using the GPT model in an electromagnetic analysis of the *Y*-junction circulator, we have confirmed the apparition of a cut-off zone in the device band-width [1], experimentally observed by How *et al.* [2]. This model has also enable us to predict the microwave response of self-biased circulators (Fig. 3) based on the use of hexaferrites set in a remanent state [23], which was not allowed by previously existing theoretical approaches.

V. Conclusion

From the *Y*-junction circulator design examples given in section 4, we have shown the simulation benefits of the GPT model. We are working on the integration of this model in a Transmission Line Matrix (TLM) method [24] for the development of an EM simulator enabling the analysis of magnetic microwave devices, whatever the magnetization of the materials is in practice. The theoretical tool we are working out should permit the optimization of the electromagnetic characteristics of magnetized material-based microwave devices taking into account at the same time, the dc field nonuniformity, the unsaturated state of certain regions of the ferrite substrate and realistic permeability tensor components values. It should enable us to predicte the response of a new generation of mm self-biased *Y*-junction circulators, tunable circuits such as filters and phase-shifters, and even miniaturized patch antennas deposited on demagnetized ferrites [25].

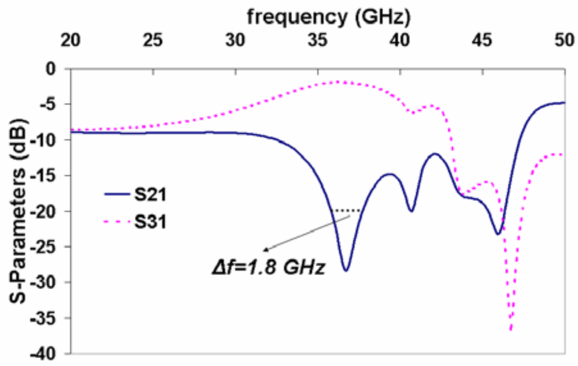

Fig. 3. Calculated S-parameters for a mm self-biased Y-junction circulator (remanent state of the hexaferrite: Mr/Ms=0.83).

VI. References

[1] A. Guennou *et al.*, *IEEE Transactions on Magnetics, 43, Sept. 2007.*

[2] H. How *et al.*, *IEEE Trans. Microw. Theory Tech.*, 47, Oct. 1999.

[3] D. Polder, *Philosophical magazine*, 40, Jan. 1949.

[4] D. Polder, and J. Smit, *Rev. Mod. Phys.*, 25(1), Jan. 1953.

[5] G.T. Rado, *Phys. Rev.*, 89, pp.529, 1953.

[6] E. Schloemann, *J. Appl. Phys.*, 41, Jan. 1970.

[7] J.J. Green and F. Sandy, *IEEE Trans. Microwave Theory Tech.*, 22, June 1974.

[8] M. Igarashi and Y. Naïto, *IEEE Trans. Magn.*, 13, N°5, Sept. 1977.

[9] J. P. Bouchaud and P. G. Zérah, J. Appl. Phys, 67 (9), 5512, 1990.

[10] P. Gelin, and K. Berthou, *IEEE Trans. Microwave Theory Tech.*, 45, August 1997.

[11] P. Gelin, P Queffelec and F. Le Pennec, *J. Appl. Phys.*, 98, n 053906, Sept. 2005.

[12] J. Smit and N.H.P. Wijn, *Philips Technical Library*, Holland, 1959.

[13] E. C. Stoner, E. P. Wohlfarth, *IEEE Trans. Mag.*, 27 (7), 1948.

[14] P. Gelin, and P. Quéffélec, *IEEE Transactions on Magnetics*, 44, Jan. 2008.

[15] J. Krupka, *IEEE Trans. Microwave Theory Tech.*, 39, July 1991.

[16] A. M. Nicolson and G. F. Ross, *IEEE Trans. on Instrumentation and Measurement*, 19, Nov. 1970.

[17] P. Quéffélec, M. Le Floc'h and P. Gelin, *IEEE Trans. on Microwave Theory and Techniques*, 47, April 1999.

[18] P. Quéffélec, M. Le Floc'h and P. Gelin, *IEEE Trans. on Microwave Theory and Techniques*, 48, August 2000.

[19] R. Marqués, F. Mesa, and F. Medina, *IEEE Microwave and Guided Wave Letters*, 10, June 2000.

[20] P. Quéffélec *et al.*, *IEEE Trans. on Microwave Theory and Techniques*, 50, Sept. 2002.

[21] W.B. Weir, *Proceedings of the IEEE*, 62, Jan. 1974.

[22] J. Lezaca, P. Quéffélec, and A. Chevalier, *International Journal of Microwave and Wireless Technologies*, Vol. 3, pp 289-294, June 2011.

[23] A. Guennou et. al., *Journal of Applied Physics*, 99, 08P505, April 2006.

[24] A. Farhat, S. Le Maguer, P. Quéffélec, and M. Ney, *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, n°8, pp. 2339-2351, Aug. 2012.

[25] F. Ferrero, A. Chevalier, J.M. Ribero, R. Staraj, J.L. Mattei, and P. Quéffélec, *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 2011.