Nonreciprocal Cell for the Broad-Band Measurement of Tensorial Permeability of Magnetized Ferrites: Direct Problem

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***Abstract*—In this paper, a broad-band characterization method for measuring the complex permeability tensor components and complex scalar permittivity of magnetized ferrites is described. The technique is based on the reflection/transmission measurement of a rectangular waveguide partly filled with the ferrite that is to be characterized. The fundamental principle of the measurement consists in using the anisotropy of the material to lead to the nonreciprocity of the device in order to have the same number of measurable parameters (the S-parameters of the cell) for the characteristics we want to determine. Here, we will recall the principle of the mode-matching method used for the electromagnetic analysis of the cell (direct problem). We will bring to the fore the difficulties linked to the determination of the complex propagation constants of the different modes and will present a calculation procedure that makes this determination in a wide-frequency range easier. We will then compare at X-band frequencies (8–12 GHz) the theoretical S-parameters with those measured for ferrites of well-known properties in order to validate the direct problem. The determination of the permittivity and permeability values from the measured parameters (inverse problem) is not addressed here.**

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

I. Introduction

In MICROWAVE devices, the implementation of signal-processing functions (phase splitting, attenuation, isolation, etc.) requires the use of anisotropic ferrimagnetic substrates in the electronic circuits. The accurate control of the performance of such a device calls for the achievement of broad-band electromagnetic characterization methods for constituent materials. Resonant methods (thus, narrow-band) permitting the measurement of permittivity or permeability tensor components of anisotropic materials may exist [1]–[3], but as far as we know, until now, no broad-band measurement method has been developed, except for diagonal tensor materials [4].

The configuration of the measurement cell used in the broad-band method that we have worked out is identical to the one used for the realization of nonreciprocal waveguide devices (isolators and commutation switches), except that there is no absorbing material in contact with the ferrite (Fig. 1). The waveguide is set in between the poles of an electromagnet to magnetize the sample. To increase the cell sensitivity, the gyrotropic effect is intensified by setting the ferrite in a circularly polarized field area of the guide with a dielectric support (Fig. 1). The advantages of the cell are linked to the waveguide rectangular technology, which is a well-proven technology. This makes the use of specific calibration procedures for the network analyzer, which are necessary for the achievement of precise measurements in high frequencies possible. Moreover, the geometry of the cell is simple, thus requiring little machining of the samples. To study a very large frequency band, several guides of different size are necessary, as we have to work in the monomodal band of each waveguide.

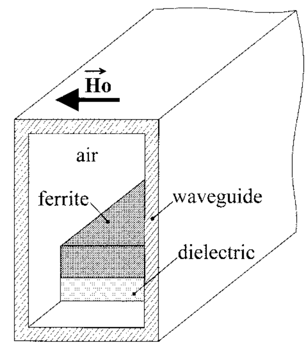

Fig. 1. Rectangular waveguide measurement cell.

II. Conditions for the Nonreciprocity of the Cell

When a uniform static magnetic field H_o is applied along the large side of the waveguide, we can notice a field displacement in the guide along the small side. However, according to the symmetry of the incident mode (transverse electric TE_{10} mode), the coupling between modes is the same whatever the wave propagation direction may be. Thus, in this case, the cell is reciprocal. When H_o is applied along the small side of the waveguide (y-axis of a Cartesian coordinate system), the field displacement occurs along the large side of the guide (x-axis) (Fig. 2). As the TE_{10} incident mode is independent of the y variable, the nonreciprocity of the field displacement along the x-axis as a function of the wave propagation direction breaks the symmetry and the reciprocity of the cell. The forward modes (wave propagated in the positive direction, as in Fig. 1) and the backward modes (wave propagated in

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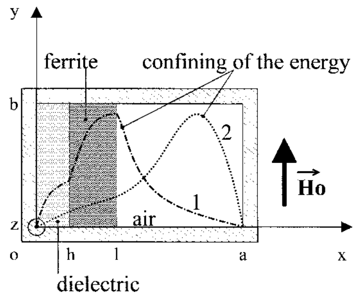


Fig. 2. Confining of the energy along the x-axis in the waveguide cross section. 1) Wave propagated in the positive direction. 2) Wave propagated in the negative direction.

the negative direction, as in Fig. 2) are not identical so that the scattering matrix elements of the cell will all be different. Thus, sufficient information is available to define specimen properties with a scattering parameter. Thus, the electromagnetic characterization of the anisotropic ferrite can be done in a single experimental phase. The condition of nonreciprocity of the cell has been proven by experimentation for different ferrites and values of the static field applied (Fig. 3), thus confirming the feasibility of the measurement technique. The data-processing program must include two different calculation procedures. The first one calculates the S-parameters of the cell as functions of the scalar permittivity ε^* and the tensorial permeability $\overleftrightarrow{\mu}^*$ of the ferrite (direct problem). The second one is an optimization procedure that permits to determine ε^* and $\overleftrightarrow{\mu}^*$ from the measured S-parameters (inverse problem). The inverse problem will be dealt with in another paper.

III. Direct Problem

The calculation of the S-parameters of the cell calls for a thorough electromagnetic analysis of the abrupt discontinuities separating the empty regions of the waveguide from the region partly filled with the ferrite. This analysis consists of first describing the electromagnetic situation (modal analysis: dispersion diagram, field patterns) on each side of the discontinuities and, second, imposing continuity conditions on the fields at the edge of the discontinuities.

A. Modal Analysis of the Cell

The cross section of the rectangular waveguide is composed of three different mediums in the loaded region (Fig. 2): the air, a dielectric layer, and the anisotropic ferrite that is to be characterized. In a $\overleftrightarrow{\mu}^*$ tensorial permeability and $\varepsilon^* = \varepsilon' - j\varepsilon''$ scalar permittivity anisotropic medium, the Helmholtz equation is written as follows:

$$\Delta\vec{H} - \vec{\text{grad}}(\text{div}\vec{H}) + \omega^2\varepsilon_o\varepsilon^*\mu_o\overleftrightarrow{\mu}^*\vec{H} = \vec{0} \qquad (1)$$

where ε_o is the permittivity of free space, μ_o the permeability of free space, Δ the Laplacian operator, and ω the radian frequency. When the static magnetic field is applied along the y-axis, the permeability tensor in the Cartesian coordinate system takes the following well-known form:

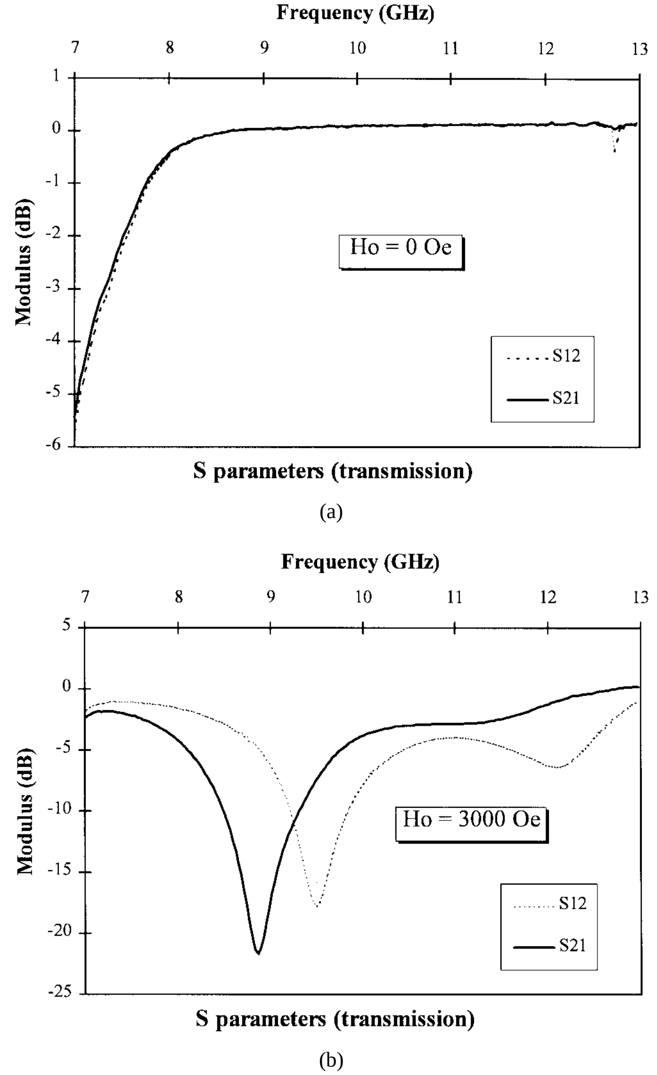


Fig. 3. Measured S-parameters of the cell loaded with a well-known ferrite. Parameters: saturation magnetization $4\pi M_s = 2386$ G.

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

where

$$\mu = \mu' - j\mu''$$
$$\kappa = \kappa' - j\kappa''$$
$$\mu_y = \mu_y' - j\mu_y''.$$

The solution to (1) can be written initially as

$$\begin{pmatrix} H_x \\ H_y \\ H_z \end{pmatrix} = \begin{pmatrix} Hr_x \\ Hr_y \\ Hr_z \end{pmatrix} \exp\left(-(k_x x + k_y y + \gamma z)\right), \qquad h \le x \le 1$$

where k_x, k_y, and γ represent the propagation constants along (Ox), (Oy), and (Oz). The continuity conditions for the field components in the $y = 0$ and $y = b$ planes (Fig. 2) lead to the following expressions for the fields in the ferrite:

$$\begin{pmatrix} E_x \\ E_z \\ H_y \end{pmatrix} = \begin{pmatrix} Er_x \\ Er_z \\ Hr_y \end{pmatrix} \sin(k_y y)\exp(-(k_x x + \gamma z))$$
$$\begin{pmatrix} H_x \\ H_z \\ E_y \end{pmatrix} = \begin{pmatrix} Hr_x \\ Hr_z \\ Er_y \end{pmatrix} \cos(k_y y)\exp(-(k_x x + \gamma z))$$

with $k_y = (n\pi/b)\ n = 0, 1, 2, \cdots$ and $h \le x \le 1$.

As the rectangular waveguide is excited by its TE_{10} mode and considering the symmetry of the discontinuities studied, the total fields in the measurement cell can be expanded in terms of TE eigenmodes [5]–[7]. These modes being independent of the y variable, we find

$$k_y = 0.$$

Thus

$$\begin{pmatrix} E_x \\ E_z \\ H_y \end{pmatrix} = 0$$

and

$$\begin{pmatrix} H_x \\ H_z \\ E_y \end{pmatrix} = \begin{pmatrix} Hr_x \\ Hr_z \\ Er_y \end{pmatrix} \exp(-(k_x x + \gamma z)), \qquad h \le x \le 1.$$

When replacing the fields with their expression in (1), we found the following matrix system:

$$\begin{bmatrix} \mu k_r^2 + \gamma^2 & -j\kappa k_r^2 - \gamma k_x \\ j\kappa k_r^2 - \gamma k_x & \mu k_r^2 + k_x^2 \end{bmatrix} \begin{bmatrix} Hr_x \\ Hr_z \end{bmatrix} = 0 \tag{2}$$

where $k_r^2 = \omega^2 \varepsilon_o \mu_o \varepsilon^*$.

The system of equations (2) has nontrivial solutions if the corresponding determinant of the system vanishes. This condition gives the dispersion relation in the anisotropic magnetic media

$$k_x^2 + \gamma^2 = k_r^2 \frac{\kappa^2 - \mu^2}{\mu}. \tag{3}$$

This is an equation of degree 2 for the k_x variable. Thus, we have two wavenumbers along the x-axis to take into account: $+k_x$ and $-k_x$. Hr_x and Hr_z appearing in the magnetic field expression are determined for each $+k_x$ and $-k_x$ wavenumber with the resolution of (2). Er_y is calculated from Hr_x and Hr_z by using the Maxwell equation

$$\overrightarrow{\text{rot}}\,\vec{H} = j\omega\varepsilon_o\varepsilon^*\vec{E}.$$

For the $+k_x$ wavenumber, we have

$$\begin{cases} Hr_x^+ = j\kappa k_r^2 + \gamma k_x \\ Hr_z^+ = \mu k_r^2 + \gamma^2 \\ Er_y^+ = -\omega\mu_o(\kappa\gamma + jk_x\mu) \end{cases}$$

and for $-k_x$, we have

$$\begin{cases} Hr_x^- = j\kappa k_r^2 - \gamma k_x \\ Hr_z^- = \mu k_r^2 + \gamma^2 \\ Er_y^- = -\omega\mu_o(\kappa\gamma - jk_x\mu). \end{cases}$$

The anisotropic magnetic medium fields are written as follows:

$$\begin{cases} H_x = [C\,Hr_x^+ \exp(-k_x x) + D\,Hr_x^- \exp(+k_x x)] \\ \qquad \cdot \exp(-\gamma\, z) \\ H_z = [C\,Hr_z^+ \exp(-k_x x) + D\,Hr_z^- \exp(+k_x x)] \\ \qquad \cdot \exp(-\gamma\ z) \\ E_y = [C\,Er_y^+ \exp(-k_x x) + D\,Er_y^- \exp(+k_x x)] \\ \qquad \cdot \exp(-\gamma\, z) \end{cases}$$

and

$$E_x = E_z = H_y = 0, \qquad h \le x \le l$$

where C and D are two integration constants to be determined.

The same study is done in the dielectric medium ($0 \le x \le h$) and in the air ($1 \le x \le a$) where two new integration constants, noted A and B, appear [7]. The continuity conditions applied for the tangential components of the fields in the "dielectric–air" and "dielectric–ferrite" interfaces lead to a four-equation system of four unknowns, which can be written in the form

$$[K][V] = 0 \tag{4}$$

where

$$[V] = \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix}.$$

The matrix $[K]$ is shown in the equation at the bottom of this page, where γ_o and γ_d are the propagation constants along the x-axis, respectively, in the air and dielectric.

The dispersion relation linking the frequency to the propagation constant for each mode is given by the eigenvalue equation

$$\det[K] = 0. \tag{5}$$

Differing forms of this equation have been given by Bresler [8] and Soohoo [9]. The field pattern of the rectangular

$$[K] = \begin{bmatrix} j\dfrac{\omega\mu_o}{\gamma_d} sh(\gamma_d h) & 0 & E_{r_y}^+ \exp(-k_x h) & E_{r_y}^- \exp(k_x h) \\ -ch(\gamma_d h) & 0 & H_{r_z}^+ \exp(-k_x h) & H_{r_z}^- \exp(k_x h) \\ 0 & -ch(\gamma_o(1-a)) & H_{r_z}^+ \exp(-k_x 1) & H_{r_z}^- \exp(k_x 1) \\ 0 & j\dfrac{\omega\mu_o}{\gamma_o} sh(\gamma_o(1-a)) & E_{r_y}^+ \exp(-k_x 1) & E_{r_y}^- \exp(k_x 1) \end{bmatrix}$$

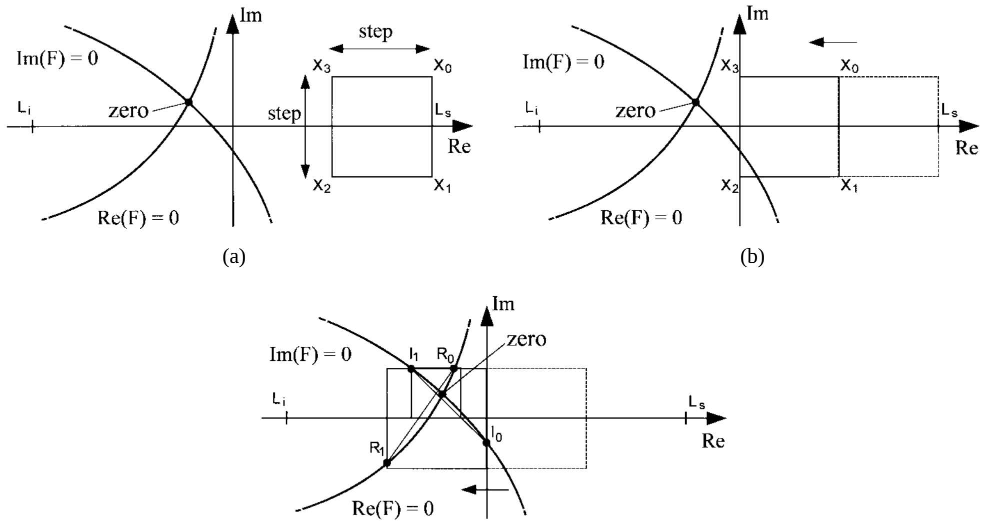


Fig. 4. Schematic representation of the calculation procedure used for the location of the roots of a complex function noted F. (a) Initialization of the calculation. (b) Systematic root search. (c) Dichotomic procedure.

waveguide is obtained by the calculation of the eigenvectors V linked to the γ eigenvalues of (5).

The main problem in the modal study presented above is the location of the complex roots of (5). Whatever losses the anisotropic magnetic medium may show, the solutions of (5), that is to say, the propagation constants of the different waveguide modes, are complex as follows:

$$\gamma = \alpha + j\beta$$

where α is the attenuation constant and β the phase constant. The calculation procedures used at first for the resolution of (5) based on the Müller's method [10] or on the ZEPLS Program [11] have proven to be ineffective in most cases. Thus, we had to realize a particular algorithm better adapted to the problem. The method consists of scanning an area of the complex plane with a square of small size to locate the region where the real and imaginary parts of the complex function studied simultaneously nullify each other [Fig. 4(a)]. The possible changes of sign in the function are not detected between the segment extremities (classical dichotomic method), but in between the vertices of a square [Fig. 4(b)]. If two changes of sign are detected for the real part as well as for the imaginary part of the function, a square four times smaller than the previous one is defined around the point of intersection of the segments R_0R_1 and I_0I_1 [Fig. 4(c)]. The process goes on until a precise value is reached for the dimensions of the square. Once a root is located, the search for other solutions continues. The calculation stops when the number of solutions is reached. Equation (5) has been written in an analytic form that does not contain any poles. In this case, the algorithm cannot mistake a pole for a zero, which both lead to a change of sign in the function.

In order to reduce the calculation time, the systematic root search in the complex plane is only applied to the first frequency value. For the upper frequencies, the solutions located at the previous frequencies are extrapolated to set a square directly around each solution. Even if the algorithm is

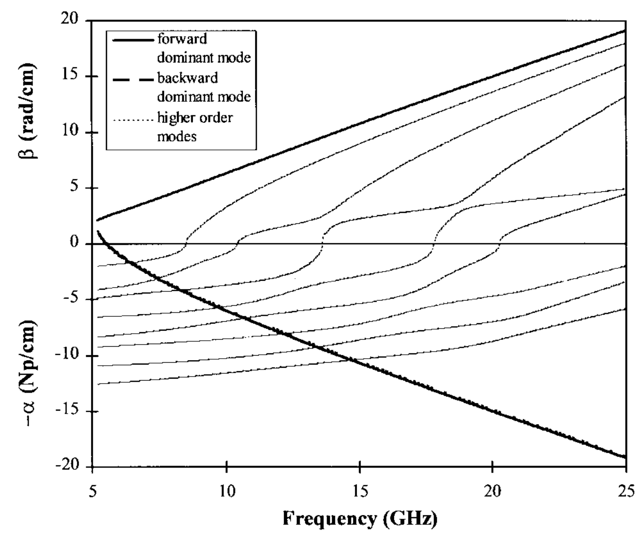


Fig. 5. Propagation constants $\gamma = \alpha + j\beta$ of the first forward modes versus frequency. Waveguide dimensions: $a = 22.86$ mm, $b = 10.16$ mm. Ferrite parameters: thickness $= 7.25$ mm, $\varepsilon^* = 14.5 - j0$, saturation magnetization $4\pi M_s = 1780$ G, anisotropy field $H_a = 180$ Oe, resonance linewidth $\Delta H = 5$ Oe. Dielectric parameters: thickness $= 0.635$ mm, $\varepsilon^* = 9.6 - j0$.

slower than the software usually used, especially for the first frequency value, it has always shown a total reliability.

To illustrate the results of the simulation software of the measurement cell, we show in Fig. 5 a dispersion diagram obtained by using the algorithm previously described. This graph, which gives the evolution in function of the frequency of the propagation constants of the first forward modes of the rectangular waveguide containing a magnetized ferrite, proves the efficiency of the algorithm in locating the complex solutions of the characteristic equation (5) on a broad frequency band. The propagation constants of the backward modes, which are solutions for (5), have not been included in Fig. 5 to improve intelligibility. On this graph, a mode is appearing for which the group and phase velocities have

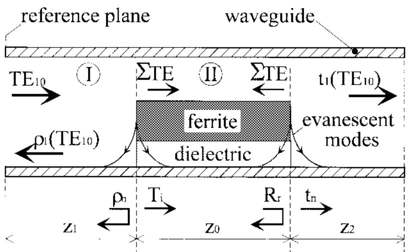


Fig. 6. Measurement cell discontinuities. Waveguide I: empty regions. waveguide II: region partly filled with the ferrite.

different directions between 5–6 GHz. Thus, the calculation of the S-parameters of the cell will have to be done with caution. This mode will be added to the backward modes since it carries some energy in the negative direction.

After the accurate calculation of the modes in each region of the waveguide and for each propagation direction, we have to match the fields for each mode at the cell discontinuities.

B. Modal Matching at the Discontinuities

In the cell, the TE_{10} mode (the dominant mode of the empty waveguide) interacts with the empty/loaded waveguide discontinuities (Fig. 6). Thus, part of the energy transported by this mode is reflected and transmitted in the waveguide, i.e., reflection and transmission of the dominant mode and excitation of propagated higher order modes, and the other part is stored in the neighborhood of each discontinuity. The energy stored corresponds to the excitation of evanescent higher order modes. As the cell discontinuity does not break the TE_{10} incident mode symmetry, the higher order modes show the same symmetry as the dominant mode. There are modes of TE type [5]–[7] resulting from the same characteristic equation as the TE_{10} mode.

When the wave is propagated in the positive direction (Fig. 6), the continuity conditions for the electric- and magnetic-field components in the plane of each discontinuity are written as follows.

1) In the $z = 0$ Plane:

$$(1+\rho_1)E_{y1} + \sum_{n=2}^{N} \rho_n E_{yn} = \sum_{i=1}^{M}(T_i E_{yi} + \sum_{r=1}^{M} R_r E_{yr} \exp(\gamma_r z_0) \qquad (6)$$

$$(1-\rho_1)H_{x1} - \sum_{n=2}^{N} \rho_n H_{xn} = \sum_{i=1}^{M} T_i H_{xi} + \sum_{r=1}^{M} R_r H_{xr}\, \exp(\gamma_r z_0). \qquad (7)$$

2) In the $z = z_o$ Plane:

$$\sum_{i=1}^{M}(T_i E_{yi}\, \exp(-\gamma_i z_0) + \sum_{r=1}^{M} R_r E_{yr} = \sum_{n=1}^{N} t_n E_{yn} \qquad (8)$$

$$\sum_{i=1}^{M} T_i H_{xi} \exp(-\gamma_i z_0) + \sum_{r=1}^{M} R_r H_{xr} = \sum_{n=1}^{N} t_n H_{xn} \qquad (9)$$

where γ_r and γ_i are the propagation constants of the rth and ith mode in waveguide II, respectively, z_0 is the ferrite length, M the number of modes taken into account in waveguide II, and N the number of modes taken into account in waveguide I.

The orthogonality of modes still holds even if the waveguide is filled with an anisotropic material [5]. The use of (6)–(9) and the orthogonality conditions between the modes enable us to determine the coupling coefficients between the modes ρ_n, T_i, R_r, and $t_n (n,\, i,\, r = 1, \cdots, N)$ after having resolved an N equations system (taking $M = N$). When the wave is propagated in the negative direction, the procedure described above can be applied again. Finally, the S-parameters of the cell are given by

$$S_{11} = \rho_1 \exp(-2\gamma_1 z_1) \quad S_{12} = t_1' \exp(-\gamma_1(z_1 + z_2))$$
$$S_{21} = t_1 \exp(-\gamma_1(z_1 + z_2)) \quad S_{22} = \rho_1' \exp(-2\gamma_1 z_2)$$

where γ_1 is the propagation constant of the dominant mode in waveguide I; ρ_1, t_1 are the coupling coefficients between the forward dominant modes and ρ_1', t_1' the coupling coefficients between the backward dominant modes.

Twenty modes have been taken into account in each region of the cell and for each propagation direction to obtain the convergence of the calculated values of the S-parameters of the cell. At the first frequency value, the central processing unit (CPU) time for the calculation of the S-parameters is 40 s using an IBM RS 6000 computer. At a given upper frequency, it is only 0.25 s since the location of the modes is faster.

At this point of the study, we can calculate the S-parameters of the cell in function of the components of the permeability tensor $\overleftrightarrow{\mu}^*$ and the scalar permittivity ε^* of the ferrite present in the guide. As our aim is to characterize materials, we now have to reverse the process, that is to say, determining $\overleftrightarrow{\mu}^*$ and ε^* knowing the S-parameters of the cell measured with a network analyzer. However, contrary to the case of the characterization methods for isotropic materials [12]–[14], it is impossible here to analytically express the electromagnetic properties of the material according to the S-parameters since the electromagnetic analysis of the cell is complex. That is why the resolution of the inverse problem requires the use of numerical optimization methods. At the moment, we are studying a calculation procedure based on the Levenberg–Marquardt algorithm [15] that seems to be really suited to solve the inverse problem. This work is not presented here, but will be dealt in a future paper. As far as we are concerned, here we will focus on the validation of the direct problem, especially in the real case, that is to say, for lossy ferrites.

IV. Validation of the Direct Problem

The validation of the direct problem consists in verifying that the S-parameters calculated with the simulation software of the cell are in accordance with the ones measured for a well-known ferrite. This analysis calls for the use of a physical model permitting us to calculate the permeability tensor components according to the static field applied during the measurement process and according to intrinsic parameters of the ferrite such as saturation magnetization $4\pi M_s$, anisotropy

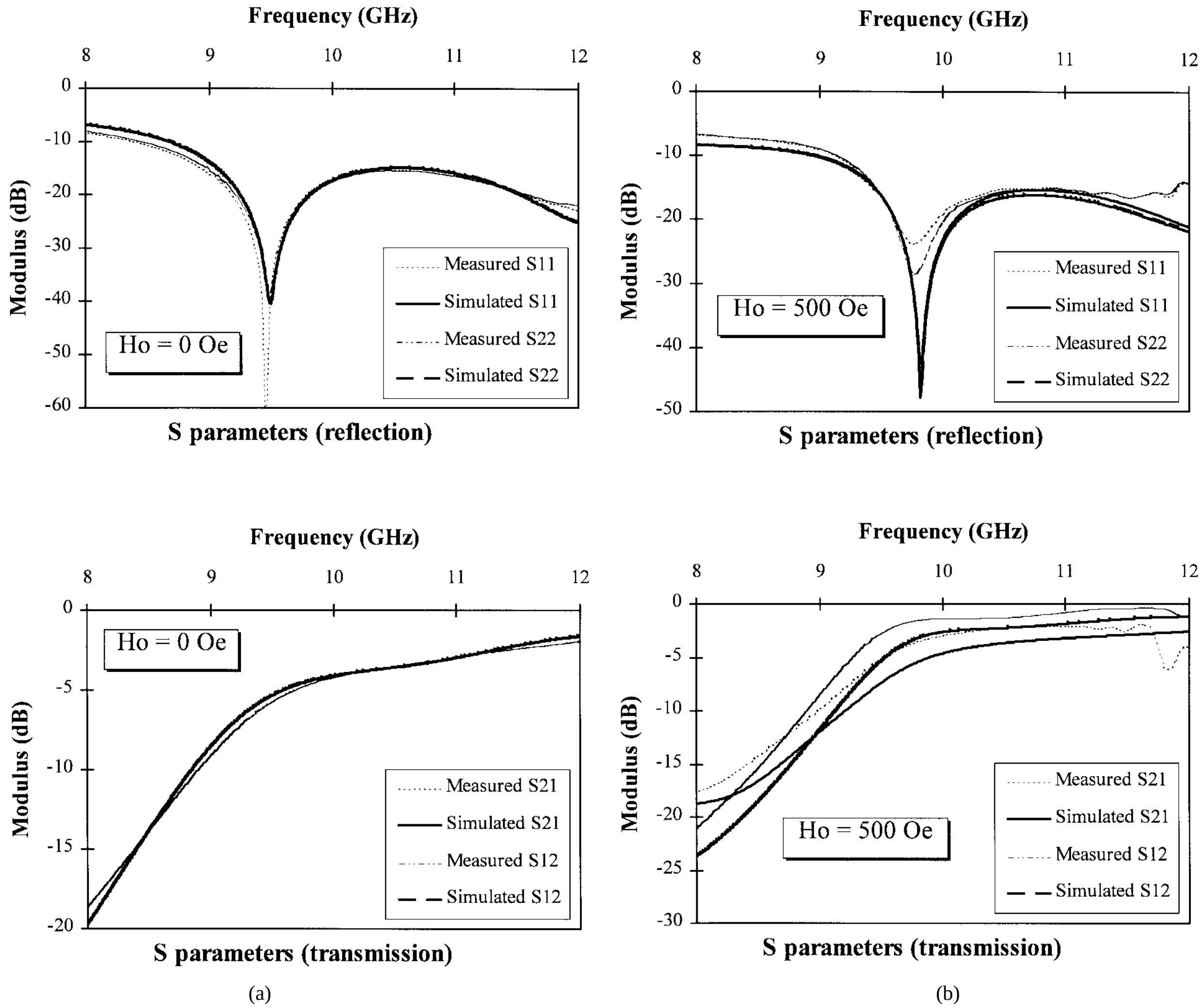
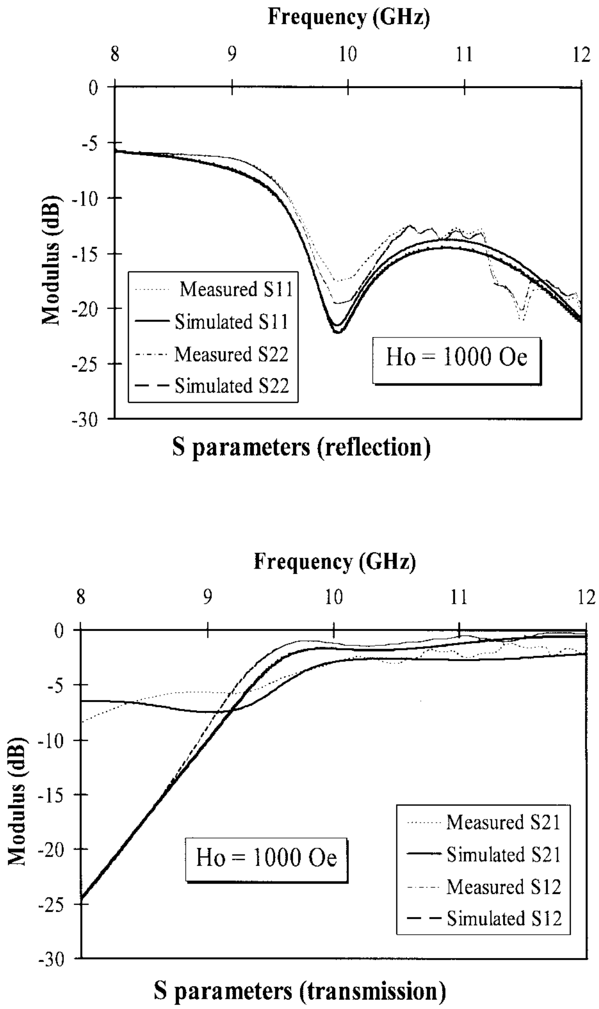


Fig. 7. S-parameters magnitude versus frequency for different values of the magnetic static field applied H_o. Ferrite under test properties: $4\pi M_s = 5000$ G, $H_a = 200$ Oe, $\Delta H = 500$ Oe. (a) Magnetic static field applied $H_o = 0$ Oe. (b) Magnetic static field applied $H_o = 500$ Oe.

field H_a, and resonance linewidth ΔH (losses) given by the sample supplier.

A simple model exists which precisely describes the behavior of a saturated ferrite in high frequencies. This is the Polder's model [16]. In a partly magnetized state, the ferrite is subdivided into Weiss domains. It is heterogeneous, thus making the calculation of the elements in the tensor $\overleftrightarrow{\mu}^*$ difficult. The models already existing [17]–[20] have the disadvantage of not presenting all the elements of the permeability tensor in a single stage or of calling for experimental corrective factors to be usable. Recently, a new statistic model for nonsaturated ferrites, which provides all the elements of the tensor $\overleftrightarrow{\mu}^*$ and which works whatever magnetization state and frequency considered, has been published [21]. This statistic model is different from the previous ones in that way that it does not consider the material partly magnetized as a whole of independent domains, but rather as a whole of independent grains composed of interactive domains. The comparison between the elements of the tensor and measurements realized in a resonant cavity [2] or with models existing in their validity domain is very satisfying. That is why we have decided to use this model for the validation of the electromagnetic analysis of our cell.

A first series of theory/experimentation comparison has been done by neglecting ferrites losses in the calculations in order to simplify the research of solutions for the characteristic equation of the waveguide. In this case, the nonreciprocity of the cell could not be brought to the fore from a theoretical point-of-view. This proves the importance of the losses in the electromagnetic analysis, which are mainly responsible for the nonreciprocity of the magnitude of the S-parameters. Since then, the new zero research procedure in the complex plane has permitted to solve the real case (lossy ferrites). In order to illustrate the experimental results obtained with an X-band rectangular waveguide (dimensions $a = 2.286$ and $b = 1.016$ cm) made of brass, in Fig. 7, we give the S-parameters measured for different values of the magnetic static field applied H_o when the cell is loaded with a ferrite of a saturation magnetization $4\pi M_s = 5000$ G, an anisotropy field $H_a = 200$ Oe, and a resonance linewidth $\Delta H = 500$ Oe. In X-band, this ferrite is situated in a high lossy zone ($\gamma 4\pi M_s = 14$ GHz, where γ is the gyromagnetic ratio). The calibration



(c)

Fig. 7. *(Continued).* S-parameters magnitude versus frequency for different values of the magnetic static field applied H_o. Ferrite under test properties: $4\pi M_s = 5000$ G, $H_a = 200$ Oe, $\Delta H = 500$ Oe. (c) Magnetic static field applied $H_o = 1000$ Oe.

procedure for the network analyzer (HP 8510B) used for the measurements is a thru-reflect line (TRL) [22].[1] These measurements prove the nonreciprocity of the measurement device. We also observe a good agreement between the measurements and simulations over a broad frequency band and for different magnetization states of the ferrite. In X-band, the theoretical and experimental S-parameters magnitudes are very close. Moreover, the measurements and simulations show the same evolution for the resonance frequency appearing in the reflection parameter. However, when $H_o = 1000$ Oe, the measurements results are disrupted at high frequencies [Fig. 7(c)]. This cannot be attributed to the magnetostatic modes resonance since these modes are taken into account in the electromagnetic analysis of the cell. The observed discrepancies are probably caused by the increased measurement errors correlated with the air gaps between the ferrite sample and waveguide walls in high magnetic-field magnitudes. A specific cell will have to be worked out in order to make the sample insertion inside the waveguide easier and to permit the use of conductive paste fillers.

The study of the cell sensitivity has allowed us to observe significant variations in the values and frequency behavior of the S-parameters when the electromagnetic characteristics of the ferrite or the magnetic static field magnitude change. This indicates a good accuracy in the theoretical results obtained and confirms the validity of the electromagnetic analysis of the cell. A good similarity between the calculations and the measurements has also been observed for other ferrites of different properties.

V. Conclusion

We have created simulation software and realized a rectangular waveguide measurement cell for the broad-band characterization of magnetized microwave ferrites. Taking into account ferrite losses in the calculations due to a new zero research procedure in the complex plane demonstrated the nonreciprocity of the device. This confirms the feasibility of the measurement technique in a single experimental phase. Moreover, the comparison of the theoretical and experimental results have permitted the validation of the direct problem at X-band frequencies (8–12 GHz). These encouraging results now enable us to consider the resolution of the inverse problem to obtain the electromagnetic characteristics of the anisotropic ferrites tested. However, since the S-parameters of the cell are nonlinear functions of the ε', ε'', μ', μ'', κ', κ'' variables and since many unknowns have to be determined, the resolution will have to be done with caution to avoid the divergence of the calculations or the convergence toward local minima of the objective function (distance between the calculated S-parameters and measured ones).

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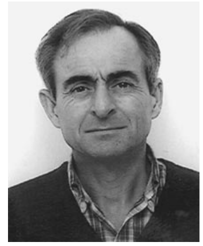

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