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Ferrite Material Characterization Using S-Parameters Data

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ABSTRACT

Since many applications rely on the knowledge of the electromagnetic material properties of ferrites, such as ferrite phase shifters, this paper presents an algorithm for characterizing ferrite materials in a single frequency using a rectangular waveguide system. In this method, the extraction of ferrite parameters is implemented through minimizing the difference between the measured data and the results from modal analysis of the system. The main advantage of this method compared to the other ones is that the proposed method only needs the amplitude of the reflection and transmission coefficients to estimate the parameters of ferrite materials. This makes the implementation easy and eliminates the problems associated with phase calibrations and measurements. This validation is achieved by simulation and experimental tests. The proposed algorithm is validated by characterizing YIG and SL-470 ferrites.

1. Introduction

Electromagnetic material characterization has long been a problem of the many designs. The goal is to extract permittivity $\epsilon\,(\omega)$ and permeability $\mu\,(\omega)$, also known as the fundamental electromagnetic parameters, as accurately as possible [1-5]. These constitutive parameters determine the effects of externally applied electromagnetic field on electromagnetic materials. Many applications rely on the knowledge of the electromagnetic material properties, such as stealth, integrated circuits, RF devices and so on. In stealth technology, the electromagnetic parameters describe how effectively a particular material absorbs a radar pulse [6]. Integrated circuits depends on new materials, and subsequently accurate knowledge of constitutive parameters, to increase the ability to transmit higher bandwidth signals as clock speeds in electronic devices continue to increase [3]. To design a RF device such as a ferrite phase shifter, an accurate knowledge of material constitutive parameters are needed [6-10]. So, material characterization is very important in electrical engineering. This paper presents the use of rectangular waveguide for ferrite material characterization. The main advantage of this method compared to the other methods, such as [1] is that the proposed method only needs the amplitude of the reflection and transmission coefficients. The proposed algorithm is validated by simulations and experimental tests.

2. Theory

A. Ferrite sample in a rectangular wave guide

As shown in Figure 1, we assume a ferrite sample which is placed symmetrically at the center of a rectangular waveguide with its dimensions as described in Table 1. It is assumed that the ferrite sample is magnetized along the y-axis. In this case, the electromagnetic parameters of the sample are expressed as [11]:

$$\epsilon = \epsilon_0 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$\mu = \mu_0 \begin{bmatrix} \mu_g & 0 & -j\kappa \\ 0 & 1 & 0 \\ j\kappa & 0 & \mu_g \end{bmatrix} \quad (2)$$

where:

$$\kappa = \frac{\omega\omega_m}{\omega_0^2-\omega^2} \quad (3)$$

$$\mu_g = 1 + \frac{\omega_0\omega_m}{\omega_0^2-\omega^2} \quad (4)$$

In (3), (4) $\omega = 2\pi f$, $\omega_0 = \mu_0 \times 2.8 \times 10^6 \times H_{dc}$ and $\omega_m = \mu_0 \gamma M_S$ and the values ϵ, κ, and μ_g are relative complex quantities. To determine these parameters in saturation state, it is necessary to determine ϵ_r *and* $4\pi M_S$.

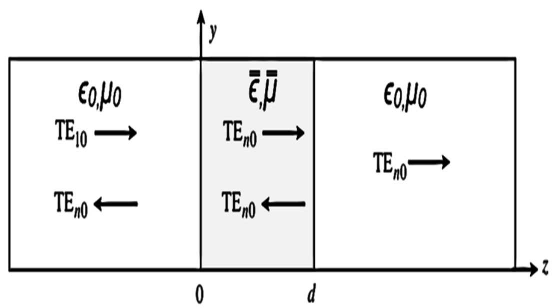

Figure 1: Side view of the problem. Left side is the input and right side is the output.

TABLE 1
THE PARAMETER OF THE PROPOSED SCHEME

Parameter	Description	Value
a, b	Waveguide dimensions	Standard values for each frequency band
d	Sample thickness	4 mm
H_{dc}	Magnetic bias	Test1: H_1 Test2: H_2

The wave equation for $H_z(x,y)$ for TE_Z fields in the sample regions is given by [3]. For TE_{n0} modes in a rectangular waveguide there is no y-dependence of the fields and hence the wave equation is expressed as:

$$[\frac{\partial^2}{\partial x^2} + (k_c^s)^2]H_z(x) = 0 \quad (5)$$

where:

$$(k_c^s)^2 = k_0^2\mu_g\epsilon_r\left(1-\frac{\kappa^2}{\mu g^2}\right) - \beta^2 \quad (6)$$

k_c^s is the cut off wave number and the superscript "S" represents the sample region.

According to the electromagnetic theory and also taking into the account the appropriate boundary conditions, when ferrite completely filling the cross-section of a rectangular waveguide transverse fields are as below [1]:

$$E_y^s(x,z) = -C_n k_{cn}^s(1-\frac{\kappa^2}{{\mu_g}^2})\, sin(k_{cn}^s x)e^{\pm j\beta_n^s z}$$

$$H_x^s(x,z) = \mp\frac{C_n k_{cn}^s}{Z_n^s}\{sin(k_{cn}^s x) \mp \frac{\kappa k_{cn}^s}{\beta_n^s \mu_g} cos(k_{cn}^s x)\}e^{\pm j\beta_n^s z} \quad (7)$$

Also, the isotropic transverse field equations from [1-3] are used to represent the fields in the empty guide region for the proposed technique. Here, only TE_{n0} modes are excited and the transverse field equations are reduced to:

$$E_y^e(x,z) = -D_n k_{xn}^e\, sin(k_{cn}^e x)e^{\pm j\beta_n^e z}$$

$$H_y^e(x,z) = \mp\frac{D_n k_{xn}^e}{Z_n^e} sin(k_{cn}^e x)e^{\pm j\beta_n^e z}$$

where superscript "e" represents the empty regions. The transverse fields in the sample region and in the empty waveguide extensions can be expanded to an infinite sum of the modal fields where the modal amplitude coefficients are determined through the enforcement of boundary conditions. The final results can be expressed in a 2N×2N matrix as given below:

$$\begin{bmatrix} D & F \\ H & J \end{bmatrix}\begin{bmatrix} A^P \\ A^n \end{bmatrix} = a_1^p \begin{bmatrix} k \\ 0 \end{bmatrix} \quad (8)$$

where D, J, F, and H are N × N sub-matrices, and K is vectors of length N. Here a_1^p is the amplitude of the incident mode and assumed to be known. These entries are all specified in the appendix.

The modal coefficients are found by solving the matrix equation above. The S-parameters of the system are given by:

$$S_{11} = \frac{A_1^n}{a_1^p} \quad (9)$$

$$S_{21} = \frac{C_1^p}{a_1^p} \quad (10)$$

B. Extraction algorithm to obtain material parameters

To characterize a ferrite sample, two sets of measurements at discrete frequencies are required for extracting three complex unknown parameters $(\mu_g, \kappa, \varepsilon_r)$ from the two complex measurements data namely, S_{11} and S_{21}. In this algorithm, only amplitude of the measurements data (S_{11} and S_{21}) is needed. Assuming that two sets of measurements are done on the ferrite sample under two different values of the applied magnetic field (H_b), then there will be two sets of data for operating frequency, mesuared S_{11}, S_{21} and simulated S_{11}, S_{21}.

Now, to extract unknown parameters, cost function error can be expressed as:

$$\text{Error} = \sqrt{\sum_{j=1}^{2}\left(\left|S^{t1}_{j1\,\text{mesuared}} - S^{t1}_{j1\,\text{simulated}}\right|^2 + \left|S^{t2}_{j1\,\text{mesuared}} - S^{t2}_{j1\,\text{simulated}}\right|^2\right)} \quad (11)$$

where t_1 refers to the test under the magnetic bias h_1 and t_2 refers to the test under the magnetic bias h_2 .

To minimize the aforementioned cost function error, a nonlinear least square inversion method can be used. The results will be the best values for the unknown parameters in the cost function $(\mu_g, \kappa, \varepsilon_r)$ and an error value (f_e).

C. Algorithm Steps

To use nonlinear least square inversion method, an initial guess for the two fundamental parameters is needed.

Then, lower and upper band vectors (l_b, u_b) according to the initial value vector (x_0) will be considered. To extract unknown parameters $(\mu_g, \kappa, \varepsilon_r)$ in the permeability tensor of a ferrite material, the process of nonlinear minimization can be started by an initial guess as below:

$$x_0 = [\text{real}(\mu_{g-guess}), \text{img}(\mu_{g-guess}), \text{real}(\kappa_{guess}), \text{img}(\kappa_{guess}), \text{real}(\varepsilon_{r-guess}), \text{img}(\varepsilon_{r-guess})] \quad (12)$$

Also, lower and upper bands can be assumed as:

$$lb = x_0 - ch \times x_0 \quad (13)$$

$$ub = x_0 + ch \times x_0 \quad (14)$$

where ch is a parameter to consider when the answer changes. After the allocation of x_0 and lb, ub, the nonlinear minimization can be done to find out the best answer for $(\mu_g, \kappa, \varepsilon_r)$. Since the permittivity of a ferrite sample changes very little over the measured frequency band, at first, the goal can be optimized to find the best answer for ε_r.

As the second step, the permittivity of the sample can be considered as a frequency independent value and the unknown parameters of the algorithm assumed to be $4\pi M_s$ and the input parameters to the algorithm are H_{dc} and ε_r. So, all the unknown parameters of a ferrite sample can then be determined.

3. Simulation Results for the YIG Sample

A. Simulation of the set up

At first, the proposed method is validated by using simulated S-parameters in CST instead of the measured S-parameters data. The YIG sample is placed in a standard Ku-band sample holder and S-parameters extracted from the coaxial ports for each magentic bias. The simulated set up is illustrated in Figure 2.

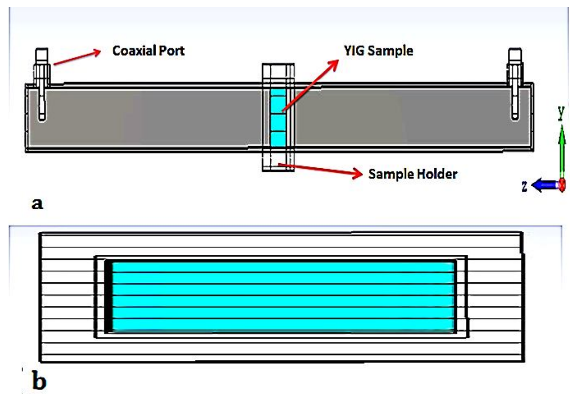

Figure 2 a: side view of the setup, b: cross section of the sample holder.

The parameters of the YIG sample in the simulation are assumed to be:

$4\pi M_s = 1280, \varepsilon_r = 14.9, H_1 = 1000$ Oe, $H_2 = 1300$ Oe

Here input parameters in the extraction algorithm are:

$$x_0 = [1, 0.05, 0.1, 0.05, \text{Epi}, 0.05]$$

$$lb = [0.5, 0.025, 0.05, 0.025, \text{Epil}, 0.025]$$

$$ub = [5, 0.075, 0.15, 0.075, \text{Epiu}, 0.075]$$

$$ch = 0.5$$

The extraction process was done at the center frequency of 15 GHz for Epi values between 10 & 18. For each Epi value, initial value vectors (x_0, lb, ub) were computed in the algorithm.

B. Results

The extracted values for ε_r at the center frequency of 15GHz are listed in Table 2.

Extracted results for ε_r show about 10% error from the exact value which is 14.9. It is clear that to obtain a better result, the initial vector value (x_0) should be choosed properly.

For the second step of characterization, the permittivity of the YIG is assumed to be the average of the extracted values in Table 2.

In the second step of the characterization of the YIG sample, the input parameters assumed to be:

TABLE 2
EXTRACTED RESULTS AT 15 GHZ FOR THE YIG SAMPLE

Epi	ε_r	Cost function error value
10	13.2	0.123
11	13.8	0.1
12	13.97	0.12
13	14.3	0.098
14	14.5	0.066
15	14.8	0.06
16	15.3	0.1
17	15.5	0.13
18	15.7	0.143

$$\varepsilon_r = 15, \quad 4\pi Ms = 4\pi Msi,$$
$$H_1 = 1000\text{ Oe}, H_2 = 1300\text{ Oe}$$

$$x_0 = [4\pi Msi]$$
$$lb = [4\pi Msil]$$
$$ub = [4\pi Msiu]$$

here, 4πMsi is changed between 800 and 5000 Gauss and the extracted values are listed in Table 3.

TABLE 3
EXTRACTED RESULTS AT 15 GHZ FOR THE YIG FERRITE

4πMsi	4πMs	Cost function error value
800	1050	0.123
1000	1100	0.1
1500	1170	0.12
2000	1300	0.098
2500	1420	0.066
3000	1510	0.06
3500	1550	0.1
4000	1600	0.13
5000	1670	0.143

Extracted results for 4πMs show that when the initial guess for 4πMs is in the range of 800-2000, the extracted value error is relatively acceptable.

So, the proper initial values for extraction are very important. For a better result, extraction process can be done for several trials and then take an average for the final values.

External magnetic bias was provided using permanent magnets. The input parameters to the algorithm at first step are listed in Table 4. The results for the first step are presented in Table 5 .

4. EXPERIMENTAL TEST

An experimental test is done on a SL-470 ferrite. The measurement set up is illustrated in Figure 3. Ferrite sample is placed in a standard Ku-band sample holder and the amplitude of the S_{11} and S_{21} are mesured by a network analyzer.

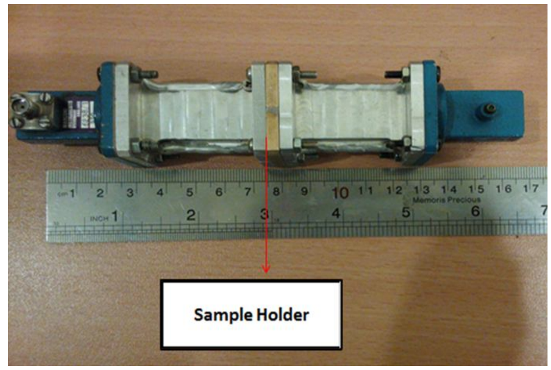

Figure 3: Measurement set up.

TABLE 4
INPUT PARAMETERS OF THE FIRST STEP FOR SL-470 FERRITE

Parameter	Value
Frequency (f)	15 GHz
Initial value vector (x_0)	[1,0.05,0.1,0.05, Epi, 0.05]
Upper band value vector (ub)	[5,0.075,0.15,0.075, Epiu, 0.075]
Lower band value vector (ub)	[0.5,0.025,0.05,0.025, Epil, 0.025]
Guess for permittivity (Epi)	Epil<Epi<Epiu
Epil	10
Epiu	18

TABLE 5
EXTRACTED RESULTS AT 15 GHZ FOR SL-470 FERRITE

Epi	ε_r	Cost function error value
10	11.2	0.231
11	12.1	0.181
12	12.88	0.151
13	13.35	0.115
14	14.1	0.045
15	14.4	0.034
16	15.5	0.124
17	15.85	0.137
18	16	0.245

It can be concluded from Table 3 that for extracted ε_r = 14.4, the cost function error value is minimum. The exact value for the permittivity of SL-470 is 14.7

[12]. In the second step, we assumed ε_r = 14.4 and the other input parameters are listed in Table 4.

TABLE 6
INPUT PARAMETERS FOR THE SECOND STEP FOR SL-470 FERRITE

Parameter	Value
Frequency (f)	15 GHz
ε_r	14.4
4πMs	4πMsi
Initial value vector (x_0)	[4πMi]
Lower band value vector (lb)	[4πMl] =1000
upper band value vector (ub)	[4πMu] =5000

Finally, the extracted results for second step are presented in Table 7.

TABLE 7
EXTRACTED RESULTS AT 15 GHZ FOR SL-470 FERRITE

4πMsi	4πMs	Cost function error value
1000	2350	0.34
1500	2740	0.321
2000	3050	0.189
2500	3330	0.154
3000	3780	0.109
3500	3900	0.097
4000	4100	0.067
4500	4400	0.021
5000	4450	0.02

The minimum cost function error value obtained in Table 7, when the extracted value for 4πMs is 4450. So, the results of this measurement for SL-470 can be summarized as reported in Table 8.

TABLE 8
COMPARISON OF THE MEASURED DATA WITH THE CATALOG INFORMATION FOR SL-470 FERRITE

Catalog value[12]	Extracted value by measurement
ε_r = 14.7	ε_r = 14.4
4πMs = 4700	4πMs = 4450

5. CONCLUSION

In this research, we discussed, simulated and implemented an algorithm for characterizing ferrite materials in a single frequency using rectangular waveguides.

In this method, the extraction of material parameters was implemented through minimizing the difference between the measured and the theoretical reflection and transmission coefficients.

The proposed algorithm was validated by characterizing YIG and SL-470 ferrites. It was shown that with proper initial vectors the error is less than 10%. Wide-band characterization and the effect of the ferrite loss will be considered in the future works by the authors.

6. APPENDIX

The matrix entries in (8) are computed as follow:

$$D_{mn} = k_{xn}^{e} \int_{-\frac{a}{2}}^{\frac{a}{2}} \sin(k_{xm}^{e}x).\sin(k_{xn}^{e}x).dx$$

$$J_{mn} = k_{cn}^{s}.(1-\frac{\kappa^2}{\mu g^2}) \int_{-\frac{a}{2}}^{\frac{a}{2}} \sin(k_{xm}^{e}x).\sin(k_{xn}^{e}x).dx$$

$$K_{mn} = \frac{k_{xn}^{e}}{Z_n^{e}} \int_{-\frac{a}{2}}^{\frac{a}{2}} \sin(k_{cm}^{s}x).\sin(k_{xn}^{e}x).dx$$

$$H_{mn} = \frac{k_{cn}^{s}}{Z_n^{s}} \int_{-\frac{a}{2}}^{\frac{a}{2}} \sin(k_{cm}^{s}x).\{\sin(k_{cn}^{s}x) + \frac{\kappa k_{cn}^{s}}{\mu g \beta_n^{s}} \cos(k_{cn}^{s}x)\}.dx$$

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BIOGRAPHIES

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Emad Hamidi, photograph and biography not available at the time of publication.

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