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A High Frequency Characterization of a Thin Film Ferrite, Application to the BaM and YIG

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Abstract: New microwave electronic technology challenges require integration of many passive components on chips. Among them, isolators and circulators are non reciprocal passive devices which contain magnetic materials. Hence, it is important to know the magnetic properties. The permeability tensor is the most important parameter to define, because it governs the interaction between the wave and the material, origin of all magnetic phenomenons. Our study consists in doing the characterization of thin film of BaM and YIG over frequency range of 0.4 to 65 GHz, shows specially gyroresonance phenomenon and finds resonance frequencies. The technique is based on the S parameters measurement of the magnetic materials with a network Analyser and a probe tester. Polder's model is used to calculate the different elements of the permeability tensor, which consider the ferrite at its saturated state. The results are discussed and compared to those obtained by using a Spectral Domain Approach (SDA).

Key words: Anisotropic media, ferrites, ferrites thin film, microwave measurement, permeability tensor

INTRODUCTION

The first experimental microwave ferrite device was demonstrated in 1949. The development of this type of devices was strongly linked to ferrite materials preparation and to the knowledge of spin interaction in ferromagnetic materials[1,2]. The behaviours of microwave ferrites devices are based on gyromagnetic property of ferromagnetic materials. Several effects can be exploited to provide non reciprocal propagation of the signal such as the Faraday rotation, the ferromagnetic resonance and the field displacement[2,3]. Many microwave components such as circulators, isolators, phase shifters or gyromagnetic filters are using materials and are always essential because there is no alternative semi-conductor based device that satisfies similar requirements at very high frequencies. Furthermore, microwave technologies are moving to higher frequencies up to 100 GHz, when high resistivity materials are needed so that ferrite remains the first choice. The behaviour of passive microwave devices is based on ferromagnetic resonance properties of ferrites materials. Magnetized ferrites are indeed anisotropic and characterized by a non symmetrical permeability tensor which is necessary to obtain non-reciprocal effects. Most passives magnetic devices need a saturated state of the ferrite or at least a magnetic polarization which is performed by permanent magnets. Our study consists on the characterization of ferrites thin films, like spinel ferrite, Barium ferrite (BaM) and garnet ferrite as Yttrium Garnet (YIG).

THEORY

To understand the origin of the anisotropy, the interaction between magnetic moments of the ferrite and a magnetic field needs to be studied. When a static magnetic field (H_0) is applied, to a magnetic material, the magnetic moments (M) and the corresponding magnetization (M) turns around the field axis with an angular velocity proportional to the magnitude of the field[4]. This phenomenon is called Larmor's precession. It is governed by a gyromagnetic Eq. of motion given by:

$$dm/dt = -\gamma\mu_0(m \times H_0) \quad (1)$$

$$\omega_0 = \gamma\mu_0 H_0 \quad (2)$$

$$\gamma = 176.10^9 \text{ rad s}^{-1}\text{ T}^{-1} (\Leftrightarrow 28 \text{ GHz/T}) \quad (3)$$

ω_0 is the Larmor precession frequency and ã is the gyromagnetic ratio. When, a microwave perpendicular field (H) is applied to the magnetic material, (its magnitude is very less than the static one), the magnetic moments tend to turn around a total field that oscillates.

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When the angular velocity of the moments reaches the frequency of microwave oscillations, the microwave energy is transmitted to the material and absorbed. As the strength of the applied field is increased, the most magnetic dipole moments will align with H_0 and M reaches an upper limit. The material is then magnetically saturated, Ms is denoted as the saturation magnetization and it's typically ranges from $4\pi Ms = 300$ to 5000 Gauss (CGS). Below saturation, ferrites materials can be very lossy at microwave frequencies and the RF interactions are reduced. Thus ferrites are usually operated in the saturated state. Several studies and various models allow the description of the material's electromagnetic behaviour; Polder's model Valerie Le Houe[5] is the simplest method that derived the components of the permeability tensor. The ferrite is considered, at its saturated state. At the equation of motion of magnetic moments (1), losses are not taken in account; Landau and Lifshitz Vincent[6] propose to rewrite the equation of motion of magnetic moments with a term having losses. The equation is given by:

$$\frac{dM}{dt} = \gamma \vec{M} \wedge \vec{B} - \frac{\lambda\gamma}{M} \vec{M} \wedge \left(\vec{M} \wedge \vec{B}\right) \quad (4)$$

The second term corresponds to losses. According to the direction of static magnetic field applied, the permeability tensor components can be written as:

$$\mu_r = \mu_{r'} - j\,\mu_r'' = 1 + (\omega_0 + j\alpha\omega)\,\omega_M/(\omega 0 + j\alpha\omega)^2 - \omega^2 \quad (5)$$

$$\kappa = \kappa' - j\kappa'' = \omega\omega_M/(\omega_0 + j\alpha\omega)^2 - \omega^2 \quad (6)$$

$$\omega_M = \gamma\mu_0 M_s \quad (7)$$

Where, ω_0 is the Larmor's precession frequency and α is the damping factor given by:

$$\gamma = \frac{m}{S} = \frac{q}{m_e} = 176.10^9\,\text{rad.S}^{-1}.\text{T}^{-1} = 28\text{Ghz/T} \quad (8)$$

$$\omega_0 = \gamma\mu_0 H_0 \quad (9)$$

m is the dipolar moment, S the magnetic spin moment, q and m_e are the electron charge and the mass, respectively.

$$\mu = \begin{bmatrix} \mu & jK & 0 \\ -jK & \mu & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \text{z axis} \quad (10)$$

$$\mu = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu & jK \\ 0 & -jK & \mu \end{bmatrix} \text{x axis} \quad (11)$$

$$\mu = \begin{bmatrix} \mu & 0 & -jK \\ 0 & \mu_y & 0 \\ jK & 0 & \mu \end{bmatrix} \text{y axis} \quad (12)$$

When the ferrite is in the saturated state $\mu_{x,y,z} = 1$, In our study, the external magnetic field is applied along the y axis.

MEASUREMENTS

Our study consist on the characterization of the barium ferrite (BaM) and Yttrium Garnet (YIG) thin films[7,8], which are put between the alumina substrate and the conductor lines as shown on Fig. 1.

These magnetic layers were made by sputtering RF technique in DIOM laboratory. To have a film showing observable magnetic properties, an annealing at 800°C is required. The measurement equipment is a probe system connected to a network Analyser working up to 65 GHz. Our experimental procedure requires three steps: the first step consists in the calibration of the network Analyser, The Open, Short, Thru and Load (OSTL), Load, Reflect and Match were used (LRM). The OSTL calibration is used when the measurement need a wide frequency range (0.4 to 65 GHz), as it is required to characterize the BaM sample. The LRM procedure can be used when the frequency range is not very wide (0.4 to 15 GHz) like for the YIG characterization. The second step consists in measuring the S parameters[9-11] of the two samples. The first measurement is made without an external magnetic field. This step showed the importance of the anisotropic field that characterizes the BaM as shown in Fig. 2. A non-reciprocal or gyromagnetic resonance phenomenon produced by the anisotropy field is observed and the resonance frequency is close to 52 GHz. Contrary to BaM behaviour, the YIG, doesn't show manisotropic field, Fig. 3.

The last step of the measurements consists in studying the external field magnitude effect over the resonance frequency. The transmission parameters of the

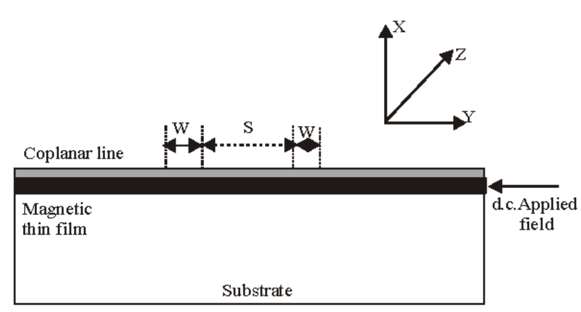

Fig. 1: Cross section of the measurement cell

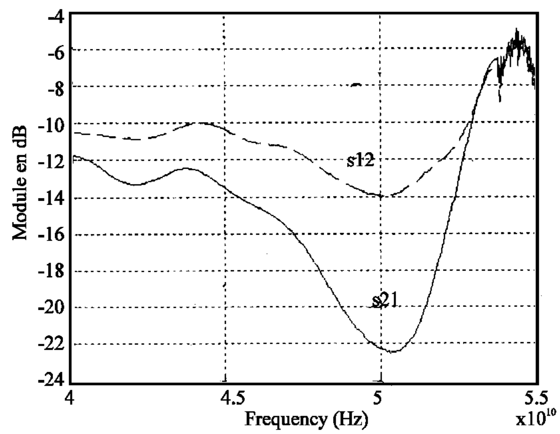

Fig. 2: Transmissions parameters S12 and S21 with $H_0 = 0$ KA m^{-1} for the BaM

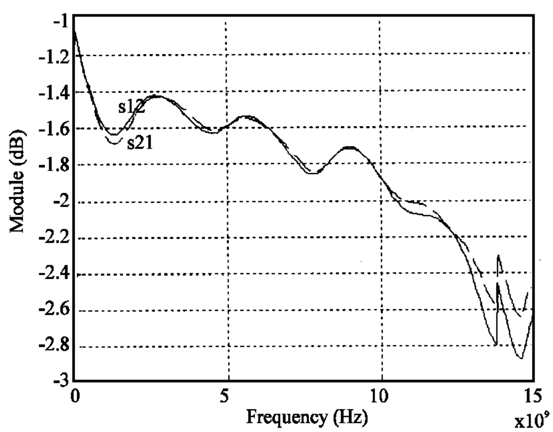

Fig. 3: Transmission parameters S12 and S21 with $H_0 = 0$ KA m^{-1} for the YIG

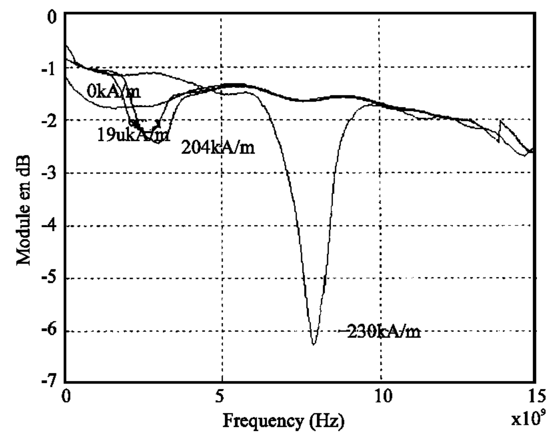

Fig. 4: Transmission parameters S12 for different values of applied field H for the YIG

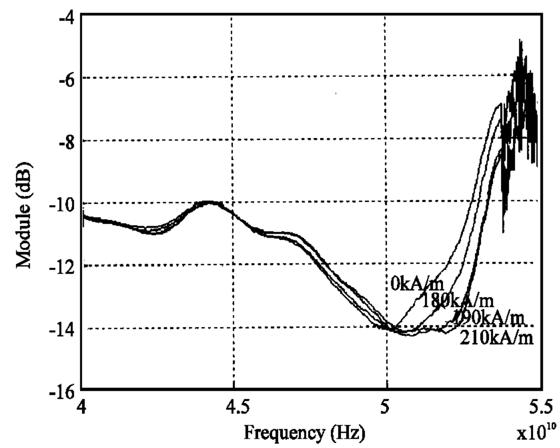

Fig. 5: Transmission parameters S12 for different values of applied field H for the BaM

BaM and YIG for several values of applied magnetic field are presented. Figure 4 shows the resonance frequency of the YIG increases when the magnitude applied field increases. It is close to 7 GHz for a 230 KA m^{-1} magnitude applied field. We can observe on Fig. 5 the effect of the BaM anisotropic field. This anisotropic field is very important compared to the external magnetic field; it is the reason why the resonance frequency slowly increases when an external field is applied, but not very much, (it close to 54 GHz for a 210 KA m^{-1}).

A new theoretical large band method was developed[6] using Polder's model determines the permeability tensor elements from the scattering parameters measured, S_{ij}. The following relations give the expression of these elements extracted from the theoretical parameters characterizing the wave propagation:

$$\mu = \frac{2}{\kappa_f^2\left(\frac{1}{(\beta^+)^2}+\frac{1}{(\beta^-)^2}\right)+\left(\beta_0-\frac{\kappa_f^2}{\beta_0}\right)\left(\frac{1}{\beta^+}+\frac{1}{\beta^-}\right)} \quad (13)$$

$$\kappa = -j\frac{\mu}{2}\left[\kappa_f^2\left(\frac{1}{(\beta^+)^2}-\frac{1}{(\beta^-)^2}\right)+\left(\beta_0-\frac{\kappa_f^2}{\beta_0}\right)\left(\frac{1}{\beta^+}-\frac{1}{\beta^-}\right)\right]\frac{\langle H_{x0}\rangle}{\langle H_{z0}\rangle} \quad (14)$$

β^+ correspond to the forward propagation constant, β^- is the backward propagation constant and β_0 is the constant propagation. when the ferrite is completely demagnetized. $K_f = \omega\sqrt{\varepsilon\mu_0}$ represent the wave number of dielectric medium with the permittivity value equal to that of the

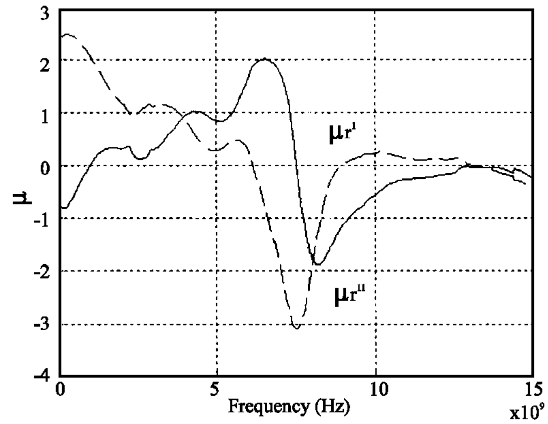

Fig. 6: Representation of μ_r'and μ_r'' for YIG

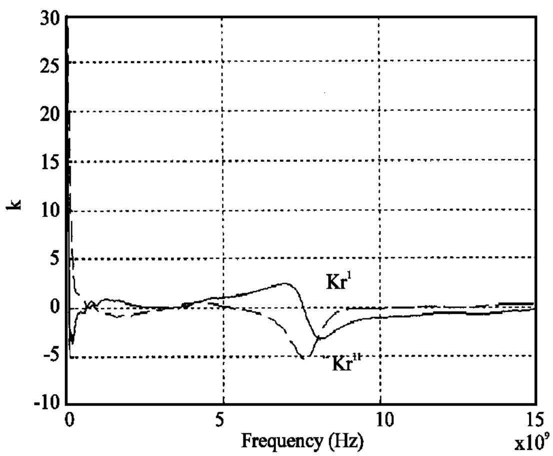

Fig. 7: Representation of K_r'and K_r'' for YIG

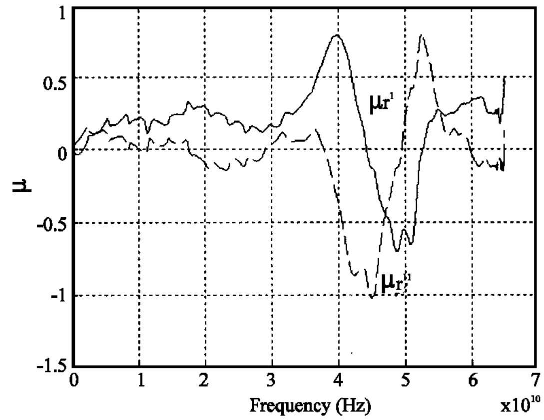

Fig. 8: Representation of μ_r'and μ_r'' for BaM

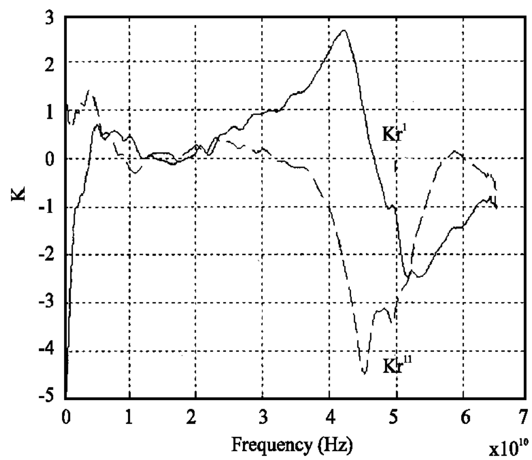

Fig. 9: Representation of K_r 'and Kr'' for BaM

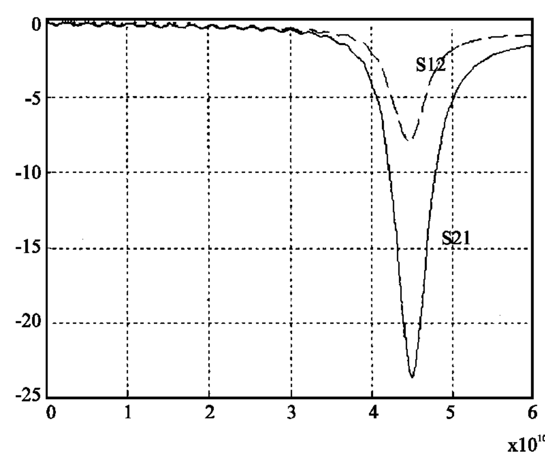

Fig. 10: Transmission parameters S12 and S21 using (SDA) for BaM

ferrite medium. The six scattering parameters measured by the analyser network are sufficient to determine these propagation constants. The equations bellow give the relations between the different parameters S_{ij} and the coefficients transmitter in the two propagation directions, T^+ and T^-.

$$\left(T^+\right)^2 S_{12} - T^+\left(S_{12}S_{21} - S_{11}S_{22} + 1\right) + S_{21} = 0$$
$$\left(T^-\right)^2 S_{21} - T^-\left(S_{12}S_{21} - S_{11}S_{22} + 1\right) + S_{12} = 0 \qquad (15)$$

$$\beta^+ = \frac{j}{L}\mathrm{Ln}\left(T^+\right)$$
$$\beta^- = \frac{j}{L}\mathrm{Ln}\left(T^-\right) \qquad (16)$$

$$\beta_0 = \frac{j}{L}\mathrm{Ln}\left(T_0\right) \qquad (17)$$

L is the ferrite sample length. At the completely demagnetized state, the device is considered symmetric and reciprocal and the S parameters are $S_{11} = S_{22}$ and

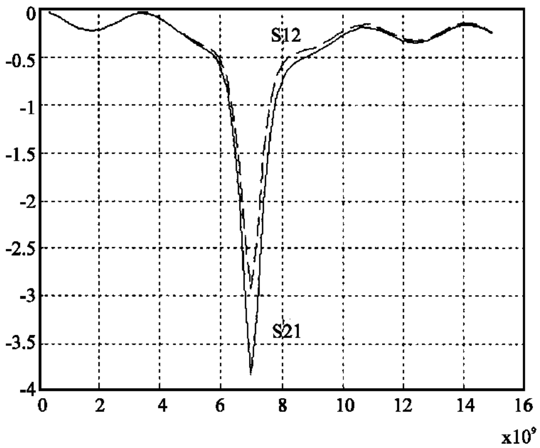

Fig. 11: Transmission parameters S12 and S21 using (SDA) for YIG

$S_{12} = S_{21}$. The ratio $\langle H_{x0} \rangle / \langle H_{z0} \rangle$ can be easily determined by a numerical simulation of the coplanar line[12]. We use a Spectral Domain Analysis (SDA) without magnetization. The experimental curves versus frequency of the tensor elements for the YIG and the BaM are presented in the (Fig. 6-9). The imaginary part for each element corresponds to losses and we observed that losses are produced at the same resonance frequency determined by the measurement of the transmission parameters.

SIMULATION

A numerical Spectral analytic method (SDA)[12,13,4] with coplanar line theory, is used. This method allows to calculate the scattering parameters S_{ij}, so the gyroresonance phenomenon are easily illustrate for the two samples. The elements of the tensor permeability μ and k considering polder's model are also determined. The simulation is made with the same conditions of experiment measurements such as: geometrical dimensions of samples, external applied field H_0 value, saturation magnetization Ms and the damping factor $\beta = 0.05$. The obtained results are shown on Fig. 10 and 11. These results are for the two samples in good agreement with experimental ones.

CONCLUSION

We have presented in this study a characterisation of ferrites materials over a large frequencies range (0.4 to 65 GHz). The permeability tensor is considered as the fundamental parameter, because it describes the interaction between the wave and the material. The resonance losses are characterized by width of the imaginary part which increases for lossy materials. The width at mid height of the curve is called linewidth and is frequently used by manufactures. This property depends on the damping factor α and on the working frequency ω: $\Delta H = 2\alpha\omega/\gamma\mu_0$. The experimental results for the YIG sample show a very narrow linewidth, (3 KA m^{-1}) that remains the best microwave material in the 1 to 10 GHz band and it can be easily saturated. The BaM sample has a high gyromagnetic anisotropy with high resonance so that no external field is needed. BaM is considered as a hard magnetic material and it is used when the magnetic device is exploited at high frequency. The simulation results delivered by the (SDA) are in agreement with experimental ones. The characterization of magnetic materials is very important in manufacturing, it deals to improve the different performances of ferrites devices, it is the reason why several researches are usually made in this domain and new large band methods for ferrites characterization are developed.

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