2022 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO) | 978-1-6654-8633-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/NEMO51452.2022.10038954

New numerical method for eigenmodes computation in ferrite stripline cavities with complex central conductor shape

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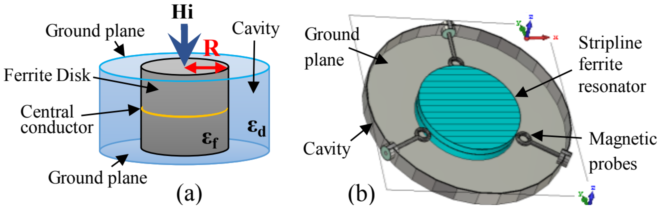
***Abstract* — This paper describes a new method for computing eigenmodes resonance frequencies in ferrite stripline cavities. Study of eigenmodes in ferrite cavities is an essential step in the design of ferrite circulators. This new method allows to determine resonant frequencies for complex central conductor shapes (i.e. different from the disk) which have never been studied analytically in the literature. In addition, calculation is nearly 1000 times faster than a 3D EM simulation, thus reducing the design time of ferrite circulators.**

***Index Terms* — Design method, eigenmodes, eigenmode chart, ferrite circulator design, resonator.**

I. INTRODUCTION

The development of microwave ferrite components such as circulators requires the study of ferrite resonant cavities. These magnetic materials with high permittivity become anisotropic when they are biased by a static magnetic field. The anisotropy is modeled by a permeability tensor and when static magnetic field is enough to saturate the material it is possible to use the Polder permeability tensor [1].This permeability model has been used to study analytically [2] simple stripline cavities, i.e. made of two ferrite disks and a central conductor in the center (Fig. 1a). These analytical models consider perfect magnetic walls assumption around disks and electric walls at the top and bottom of the structure. This model allows to study eigenmodes only by considering that central conductor between the two ferrite disks is a metal disk with same diameter as ferrite disks.



(a) (b)

Fig. 1. Schema of a stripline ferrite cavity (a) and numerical model with magnetic probe for eigenmodes study (b)

Various works on ferrite circulators have shown the interest of modifying the shape of this central conductor. For the purpose of widening the operating bandwidths in single-band [3] and also choosing the ratio between the operating frequencies in dual-band [4].

Moreover, to study eigenmodes in stripline ferrite resonators, a numerical method [5] based on cavity fed by magnetic probes has been developed. Indeed anisotropic materials are not supported by commercial 3D EM eigenmodes solver.

The new method presented in this paper provides computation resonant frequencies of eigenmodes in stripline ferrite cavities with any random central conductor. These frequencies are found for a wide range of configurations and calculation is nearly 1000 times faster than the EM simulation of the model in Fig. 1b.

The first part of the paper deals with the generation of a charts library of eigenmodes in ferrite cavities. The second part presents the calculation of resonant frequencies using charts for a central disk conductor and a WYE conductor. Finally this methodology is compared to the analytical method and to 3D EM simulations.

II. CONSTRUCTION OF A CHARTS LIBRARY FOR EIGENMODES IN STRIPLINE FERRITE CAVITIES

Saturated ferrite's permeability is characterized by Polder tensor (1) [1]. The μ and κ terms of this tensor depend on several parameters, the internal static magnetic field Hi, the saturation magnetization of the material Ms, a loss factor ΔH and the frequency.

$$\bar{\bar{\mu}}_r = \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

From Polder expression [1], anisotropy factor $|\kappa/\mu|$ is defined, and the wave number become :

$$k = \omega \sqrt{\varepsilon_0 \varepsilon_r \mu_0 \left(\frac{\mu^2 - \kappa^2}{\mu} \right)} \tag{2}$$

Then, variable $x = k \times R$ is defined as the product of k wave number and R radius of the considered ferrite disks [2].

Eigenmodes charts in stripline ferrite cavities with a complex central conductor are therefore charts of the variable x as a function of the anisotropy factor. These charts was first used in 1962 by H.Bosma in [2] and they allow determining resonance frequencies whatever resonator properties (radius, magnetization, static magnetic field, permittivity). However, modes evolution in [2] is drawn from an analytical expression. Simplifications on the boundary conditions were therefore made and the calculated chart is valid only for a central conductor disk with the same radius as ferrite disks.

Thanks to the numerical model with magnetic probes Fig. 1b ([4], [5]) it was possible to define a method of chart computation for different central conductors. It consists of

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defining a large number of resonators to cover the whole useful area for ferrite circulator design. All these resonators are simulated under CST Studio Suite using the magnetic probes design (Fig. 1b). Then a program is developed to recover the resonance frequencies from the simulations, to convert them into x and $|\kappa/\mu|$ values and to reconstruct a chart.

In order to consider the whole area useful to circulation function in weak field area [4], the chart must include values of $|\kappa/\mu|$ from 0 to 1. For this purpose, a number N of simulations with the magnetic probes model is performed. For these simulations, ferrite disks radius is set to 6 mm, permittivity to 15 and magnetization and static magnetic field values are changed between each simulation to cover a large area of the chart with the most uniform distribution as possible. Fig. 2 shows the evolution of x versus $|\kappa/\mu|$ for each simulation with $N = 20$ (blue curves).

For each of the N resonators an electromagnetic simulation is performed. The chosen model is the one with magnetic probes presented in Fig 1b. The simulation inputs (magnetization, static magnetic field, permittivity, radius of the ferrite disks, minimum simulation frequency, maximum frequency, ...) are driven in the simulation software by a Matlab program that has been developed. Indeed, this program allows to automatically assign settings, launch simulation and to recover S-parameter files from each of the N simulations.

From the S parameter Touchstone files, the Matlab program allows to find frequencies of each peak of S_{11} corresponding to the eigenmodes resonant frequencies. These frequencies can then be converted to values of x and $|\kappa/\mu|$ using equation (2), Polder's expressions for κ and μ [1] and using the parameters (magnetization, static magnetic field, ...) of each simulation.

The program therefore will compute several values of x and $|\kappa/\mu|$ for each S-parameter file and thus for each simulation. Fig. 2 shows the all samples computed using a central conductor disk and with $N = 20$ (red crosses).

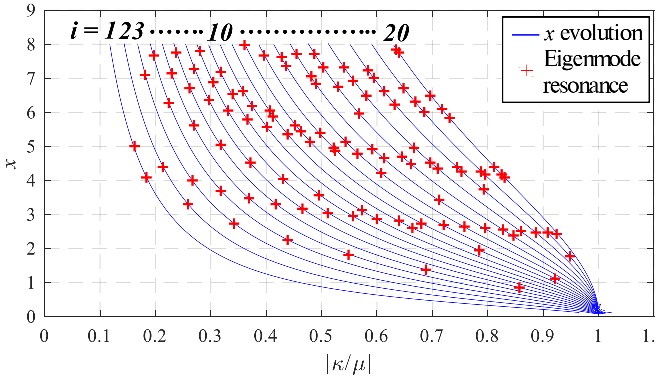

Fig. 2. Eigenmodes resonances computed with Fig. 1b model and for $N = 20$ simulations and evolution of x versus $|\kappa/\mu|$ for these N simulations

Finally, a program to reconstruct charts is developed. In fact, this program allows the generation of eigenmodes x curves versus $|\kappa/\mu|$ (Fig.3) from the scatter plot obtained in Fig.2. An example of eigenmode evolution with a disk conductor is depicted in Fig.3.

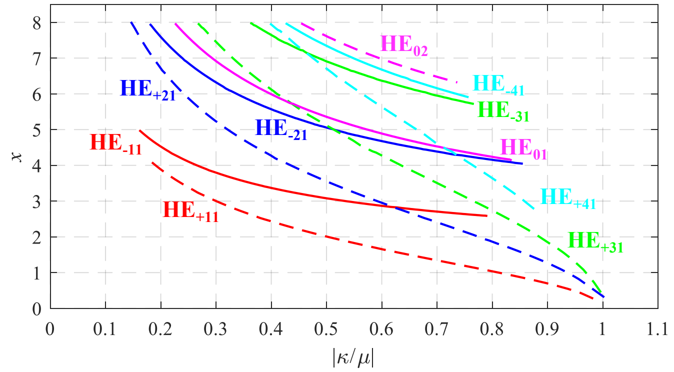

Fig. 3. Eigenmode chart computed with numerical model for central conductor disk (computed with $N = 200$)

Chart of Fig. 3 is only valid for a central conductor disk with the same diameter as the ferrite disks. To compute a chart for a different central conductor it is necessary to modify it in the 3D model of Fig. 1b. Then, the same procedure of chart computation can be done and Matlab programs developed can be reused.

A library gathering charts of different resonators was then established. It is composed of central conductor disk, WYE, WYE with stubs and triangle charts. For each conductor several charts were calculated choosing different ratios between radius of the ferrites and dimensions of the central conductor.

III. EIGENMODES RESONANT FREQUENCIES COMPUTATION AND RESULTS COMPARISON

In order to use the chart library to design ferrite circulators, a program is developed to compute the resonance frequencies of the different modes for a specified resonator.

The first step of the program is the computation of values of x and $|\kappa/\mu|$ for a wide range of frequencies using the ferrite properties specified (Hi, Ms, R, ε_r and ΔH), κ and μ expression [1] and (2). Then the evolution of x versus $|\kappa/\mu|$ obtained is plotted on the chart of specified central conductor.

Finally, the program determines index of the sample of intersection between the evolution of x and the curve of each mode. Sample's index allow to get back to the frequency.

A. Resonator with central conductor disk

As an example a resonator with a disk as central conductor was selected. Resonator's properties are $Ms = 1950$ G, $\varepsilon_r = 15.4$, $Hi = 700$ Oe and $R = 2.2$ mm. Resonant frequencies are determined using intersections samples between eigenmodes of Fig. 3 chart and evolution of x versus $|\kappa/\mu|$ for the specified resonator.

Table I shows computed resonance frequency results using our new method, using EM simulation and using the analytical Bosma's method [2].

Frequencies calculated using charts are close to those calculated using the EM simulation software. Indeed, error rate between these values are between 0.2% and 5.9% and the average deviation is 2%. The calculated chart gives better results than the analytical Bosma’s method [2] where deviations are between 0.2 and 13.2%.

TABLE I

RESONANT FREQUENCIES COMPARISON

	Chart result (GHz)	EM result (GHz)	Bosma’ s result (GHz)	Chart/EM deviation (%)	Bosma/EM deviation (%)
f_{HE+11}	9.41	10.01	8.77	**5.9**	**13.2**
f_{HE-11}	13.63	13.71	13.48	**0.6**	**1.7**
f_{HE+21}	16.90	17.82	15.38	**5.2**	**14.7**
f_{HE-21}	20.17	20.73	19.62	**2.7**	**5.5**
f_{HE01}	21.94	21.32	NA	**2.8**	**NA**

B. Resonator with central conductor WYE

For each chart calculated using a central conductor different from the disk, ratios between dimensions are defined. For the WYE central conductor there is only two dimensions the radius *R* of the ferrite disks and the linewidth *W* (Fig. 4). During calculation of each chart of this conductor shape, those dimensions are fixed leading to one charts for each *W*/*R* ratio between 0.08 and 0.8.

For a validation of our method with a WYE central conductor, the resonator with the following properties was choose : Ms = 800 G, ε_r = 14, Hi = 600 Oe, R = 5 mm and W = 2.19 mm.

With this resonator the *W*/*R* ratio is 0.44 so the chart of the WYE central conductor with a 0.44 *W*/*R* ratio should be used. On this charts the evolution of x versus $|\kappa/\mu|$ should be plotted using κ and μ expression [1] and (2). Chart and evolution of x are represented Fig. 4.

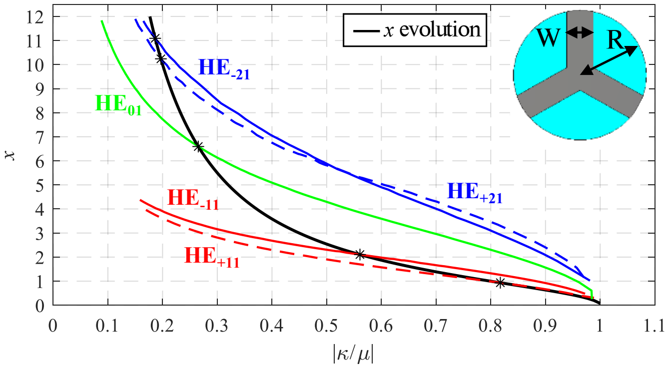

Fig. 4. Eigenmode chart for central conductor WYE with *W*/*R* = 0.44, evolution of x for specified resonator and central conductor shape

As for the central conductor disk, resonant frequencies are determined using intersection between evolution of x and eigenmodes evolution. Results are summarized on Table II.

Frequencies calculated using the chart are close to those calculated with the EM model. Deviations are between 0.2 and 3.3% with an average deviation of 1.5%. For this circulator no comparison with a literature method was made because to the authors' knowledge there is no valid analytical method for this central conductor shape.

TABLE II

RESONANT FREQUENCIES COMPARISON

	Chart result (GHz)	EM result (GHz)	Chart/EM deviation (%)
f_{HE+11}	4.30	4.26	**0.9**
f_{HE-11}	5.27	5.26	**0.2**
f_{HE+21}	11.98	11.59	**3.3**
f_{HE-21}	12.60	12.29	**2.8**
f_{HE01}	9.21	9.19	**0.2**

VI. CONCLUSION

In this paper a method to compute resonant frequencies of eigenmodes in ferrite stripline cavities has been presented. The method is based on the use of eigenmodes charts. The process to compute charts was presented, it allows the development of a chart library for different central conductor shapes. Computation method is applied to a resonator with a disk as central conductor and then with a WYE.

Frequency results obtained from the numerical chart are good and for the central conductor disk, results are closer to EM simulation than the analytical method.

Finally, a considerable time saving is achieved compared to EM simulation. Indeed, this new method allows to compute resonant frequencies in a few hundred milliseconds against around 5 minutes for an EM simulation. This computation method could thus allow the acceleration of development time for ferrite circulators. And in particular dual-band circulators which until now required long parametric studies under 3D EM solver [4].

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