FDTD ANALYSIS OF MICROWAVE CIRCULATORS INVOLVING SATURATED MAGNETIZED FERRITES

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ABSTRACT

A three-dimensional FDTD approach for the analysis of microwave circulators is presented. The underlying theoretical fundamentals are introduced, including a model for saturated magnetized ferrite material. The detrimental effect of demagnetizing fields is examined and evaluated for several examples. The simulated scattering characteristics are compared with experimental results.

INTRODUCTION

With the rising importance of mobile communication networks, increasing interest is devoted to microwave circuit technology, in particular the enhancement of ferrite based components such as circulators. As the development of advanced circulator devices is subject to empirical research in many respects, the use of numerical analysis algorithms such as the finite difference time domain (FDTD) approach yields essential benefits regarding the design process.

FDTD is based on Yee's discretization scheme [1]. It incorporates several advantages over competitive frequency domain methods, as it is an explicit scheme that does not require matrix inversions and does not yield unphysical solutions (spurious modes). The field distribution is calculated fully vectorial while selfconsistently including reflection and fringing effects. A broadband frequency response can be obtained out of a single simulation run. Furthermore, FDTD shows great flexibility concerning its suitability for different structure geometries.

Here we focus on the analysis of microwave circulator structures with an extended FDTD scheme that is capable of modeling saturated magnetized ferrite media. Aspects regarding stability, boundary conditions, the evaluation of scattering parameters and the influence of inhomogeneous demagnetizing fields are addressed. Finally, several calculation results are discussed.

THEORY

Modeling magnetized Ferrites: For microwave frequencies, electric material dispersion effects can be neglected. The permittivity is therefore assumed isotropic. The magnetic flux density follows $\vec{B} = \mu(\vec{H} + \vec{M})$, where the influence of a magnetic DC bias field on the ferrite magnetization $\vec{M}$ is described by the equation of motion originally introduced by Landau and Lifshitz, which provides an appropriate description of saturated magnetized ferrite media that includes losses near the resonance frequency.

A small signal approximation is applied with time dependent quantities considered small compared to static ones, and the linearized equation is inserted into the FDTD scheme. This requires interpolation of magnetic field components which are not directly available due

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to their location in Yee's discretization cell. Considering the boundary of the ferrite structure, an interpolation of all components as proposed in [2] carries the risk of field discontinuities due to the sharp permeability change across the ferrite's boundary. Calculation results show that this may cause instability for certain structures.

A solution that utilizes additional discretization points for the magnetic field strength and interpolation only for the flux density was introduced in [3]. Although originally proposed exclusively for ferrite-to-metal boundaries, we successfully applied a similar approach to the complete boundary of the ferrite region. In case the Courant stability condition is satisfied, the resulting stability factors are located close to the unit circle and do not show significant dependency concerning time discretization.

The calculation space is bounded by a modified perfectly matched layer (PML) absorber with unsplit field components based on pseudo source terms [4].

Calculation of Non-Uniform Inner Field Distributions: Usually ferrites are magnetized using a homogeneous DC bias field. In general, the assumption of an also homogeneous static field $\vec{H}_i$ inside the ferrite is inappropriate for arbitrary device geometries, so the inclusion of demagnetization effects becomes necessary.

Therefore, the inner magnetic field is obtained from the magnetic static field equation solved via the finite difference (FD) method or the finite integral technique (FIT), respectively. Calculation results show that the lateral field components are negligible, so $\vec{H}_i$ is considered quasi-vertical with a dominant nonzero y component H_i. Ferrite media with high saturation magnetizations show distinct radial dependency of $H_i = H_i(r)$, which is examined in our examples.

EXAMPLES

The simulation model is applied to the analysis of a triplate Y-type circulator (fig. 1) with all ports matched. Metal strips are modeled as perfectly conductive material. Relative permittivities $\varepsilon_s = 9.4$ for substrate regions and $\varepsilon_f = 12.9$ inside the ferrite are assumed. The ferrite is further characterized by a saturation magnetization of $M_s = 78$ kA/m and an inner field of $H_i = 200$ kA/m. A normalized Gaussian pulse with a width of 15 ps and a 45 ps delay is injected at port 1.

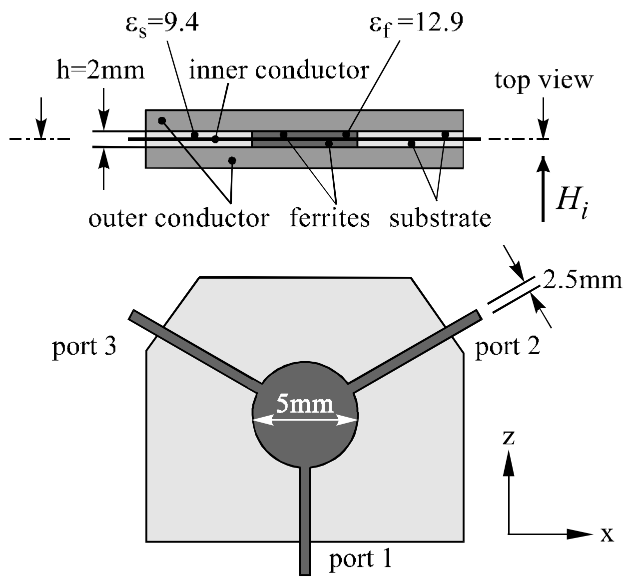

Figure 1: Y-type triplate circulator structure

The magnitude of the scattering parameters for a large frequency range are depicted in fig. 2. The range from 5.0 to 8.0 GHz (marked as "1") exhibits most distinct circulation behavior as maximal transmission $|s_{21}|$ is combined with rather small reflection $|s_{11}|$ and isolation $|s_{31}|$ parameters.

The range from 8.0 to 12.0 GHz (marked as "2") also shows circulation characteristics with $|s_{31}|$

as the transmission and $|s_{21}|$ as the isolation, but as the maximum transmission is not as high as in the first case, the further analysis concentrates on the first frequency window.

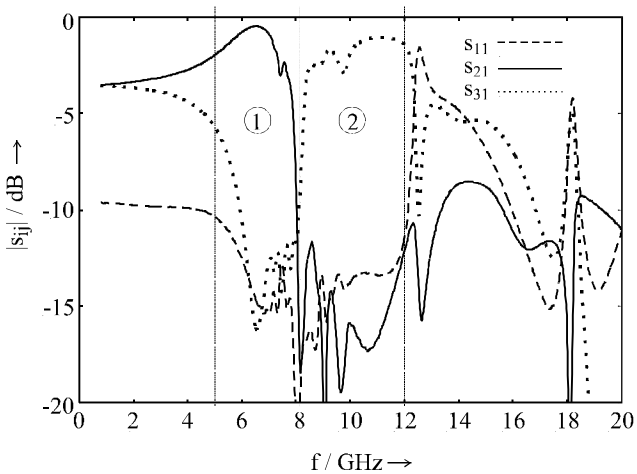

Figure 2: scattering parameters obtained over a large frequency range

At first the structure is calculated with different vertical discretization densities from 4 to 10 grid points. As the results show distinct convergence for increasing discretization densities, 8 to 10 vertical grid points can be considered to be appropriate. Secondly the substrate height is increased from 1.0 mm to 1.5 mm and 2.5 mm. The scattering characteristics obtained for each case exhibit remarkable differences, which is illustrated e. g. for the reflection in figure 3. Therefore the substrate height obviously has to be considered, and two-dimensional calculation approaches which often neglect vertical dependencies may yield essential disadvantages concerning accuracy compared to their three-dimensional counterparts.

Finally the error is analyzed that arises if a uniform static field distribution is assumed inside the ferrite compared to an inhomogeneous static field distribution. Two examples are considered with saturation magnetizations of $M_s = 100$ kA/m and $M_s = 200$ kA/m which correspond to a radial field increase of about 7 % and 20 %, respectively.

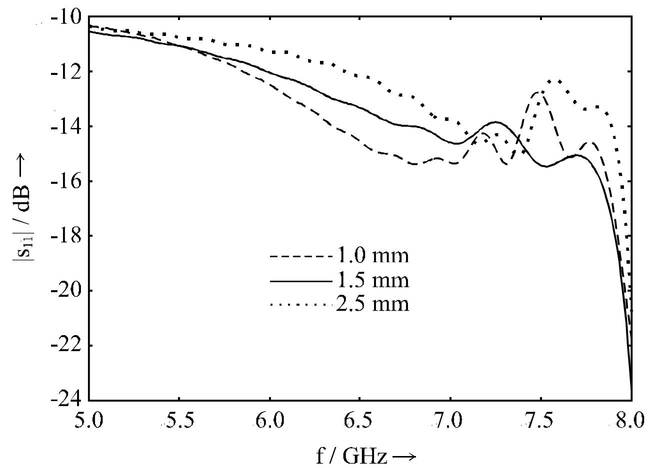

Figure 3: reflection parameter for different substrate heights

The calculated scattering parameters show that the uniform field assumption can be considered suitable for the first case within the frequency range of interest, while in the second case the results obtained from a uniform field assumption show distinct deviations from those assuming a non-uniform distribution. Figure 4 depicts the characteristics obtained for both assumptions in the second case with $M_s = 200$ kA/m.

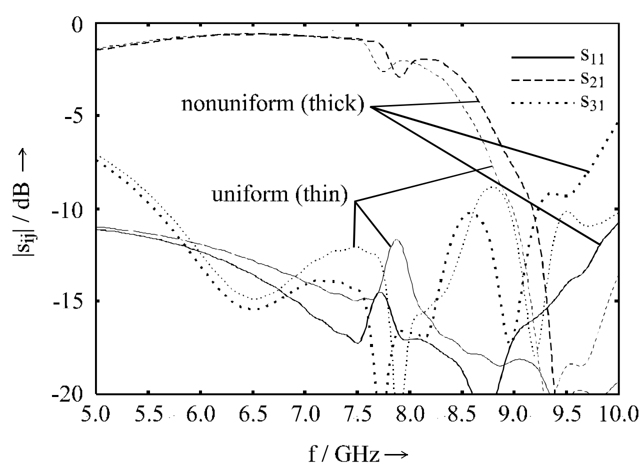

Figure 4: scattering parameters for uniform and non-uniform magnetic field distribution

For verification of the simulation model, a circular microstrip resonator structure according to figure 5 is analyzed via both a computer simulation and corresponding experimental measurements.

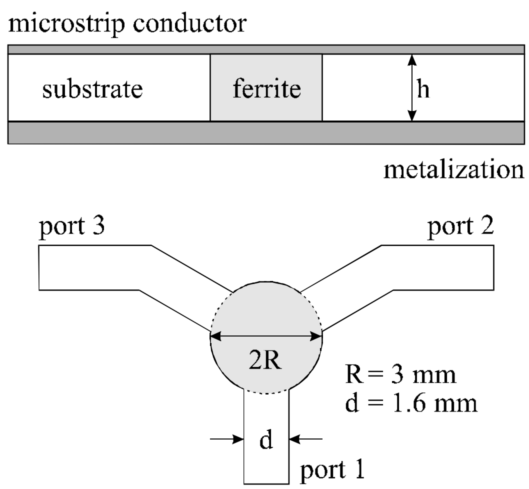

Figure 5: ferrite loaded microstrip resonator

The substrate height is $h = 1$ mm, and the permittivity is set to $\varepsilon_s = 5.4$ for the substrate and $\varepsilon_f = 14.8$ for the ferrite. A saturation magnetization of $M_s = 80$ kA/m and an inner field of $H_i = 55$ kA/m are chosen. The simulated and measured scattering characteristics are depicted in figure 6.

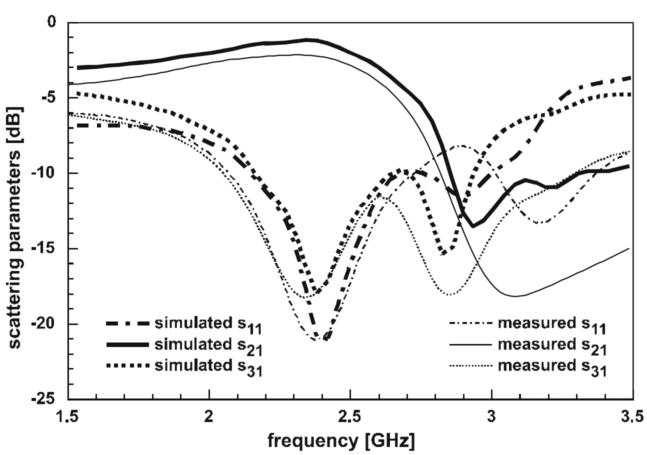

Figure 6: comparison of simulated and measured scattering characteristics

As the corresponding simulated and measured curves show good qualitative and quantitative agreement over the frequency range of interest, the simulation model is considered suitable for the analysis of ferrite loaded circulator circuits.

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