

Co-Simulations of DC Magnetic Bias Fields and RF Performance for Microwave Ferrite Circulators

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Abstract—This paper presents finite element co-simulations for DC magnetic field and microwave non-reciprocal performance of ferrite circulators. Permanent magnets provide a DC bias field, but need to be large for a uniform magnetic field distribution inside the ferrite material. Additionally, the ferrite effective permeability is a nonlinear function of magnetic bias. Smaller magnets give a non-uniform bias field distribution, which can be taken into account in the full-wave simulations. To demonstrate the effect of this nonuniform bias, a commercial ferrite material from Skyworks (TT105) is chosen for a circulator design around 3.9 GHz assuming first a uniform DC magnetic field that saturates the ferrite. A small commercial rare-earth permanent magnet is then simulated to obtain the nonuniform static magnetic field in the ferrite, and resulting HFSS simulations show that the effects of nonuniform bias field on circulator performance can be predicted using a combination of analysis methods.

Index Terms—Circulator, ferrite, permanent magnet, isolation

I. INTRODUCTION

Circulators are non-reciprocal components that have been used for a long time in microwave systems to, e.g. isolate a receiver from a transmitter. Standard design approaches for circulators with saturated magnetic materials are described in [1]. Externally biased ferrite circulators were first examined in the 50's, e.g. [2]. Microstrip and stripline circulator design has been explored to a limited degree in, e.g., [3], [4]. However, although a few publications consider full-wave simulations using non-reciprocal materials [5], simulations of the external DC magnetic bias field are lacking.

In this work, we show in simulations how the DC magnetic bias field of small permanent magnets varies as a function of position and size. The resulting non-uniform field can be applied to a ferrite disk and microwave performance simulated. The geometry of such a circulator is shown in Fig.1. The ferrite disk is embedded in a microstrip substrate, with the permanent magnet placed directly above. Ansys Maxwell is used for the static simulations, while HFSS is used for the full-wave electromagnetic analysis. The nonlinearity of the ferrite is taken into account with a calculated effective permeability as a function of applied bias field. For a 3.9 GHz circulator design, a comparison is performed between a fully saturated ferrite and one with a non-uniform DC bias from a small permanent magnet.

II. B-FIELD OF A CYLINDRICAL PERMANENT MAGNET

Cylindrical magnets are easily found commercially and have a symmetry compatible with commercially available ferrite pucks, e.g. [6]. The estimate of the z -component of the

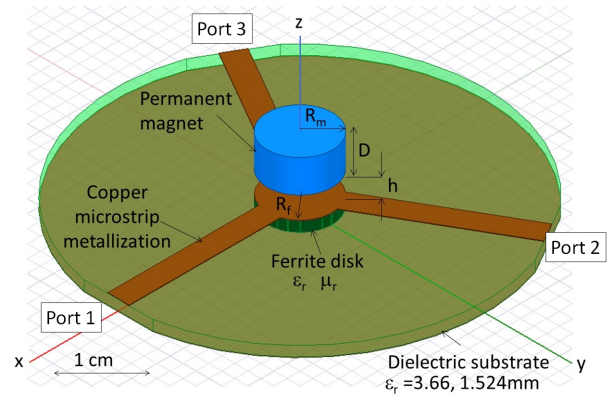


Fig. 1. Layout of microstrip circulator showing a permanent magnet that provides DC bias and a ferrite cylinder.

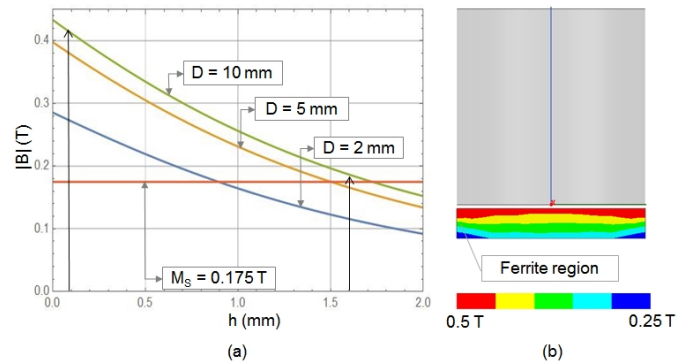


Fig. 2. (a) Calculated B-field magnitude versus distance for a permanent cylindrical magnet (embedded in air) with $D = 2, 5$ and 10 mm. (b) Simulated results for $D = 10$ mm, $R_m = 5$ mm and $h = 0.1$ mm.

magnetic flux density vector of a cylindrical permanent magnet shown in Fig.1 along its axis is given by [7]:

$$B(z) = \frac{B_r}{2} \left(\frac{z}{\sqrt{z + R_m^2}} \right) - \left(\frac{z - D}{\sqrt{(z - D)^2 + R_m^2}} \right) \quad (1)$$

where B_r is the remnant flux density, and D and R_m are the magnet thickness and radius. Fig.2 shows $|B(z)|$ for different commercially available magnet thicknesses D , with $R_m = 5$ mm and $B_r = 1.2$ T [8]. The red line shows the magnetization M_s required to fully saturate the ferrite.

Starting from this one-dimensional theoretical estimate, three-dimensional static finite element simulations for $|\vec{B}|$ are performed in Ansys Maxwell. First, the nonlinear ferrite characteristics are taken into account by calculating the effective

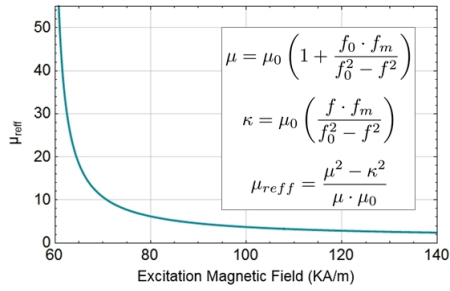


Fig. 3. Effective relative permeability versus magnetic bias field intensity. Relevant parameters: $f_0 = 3.8\text{GHz}$, $M_s = 0.175\text{T}$ [9].

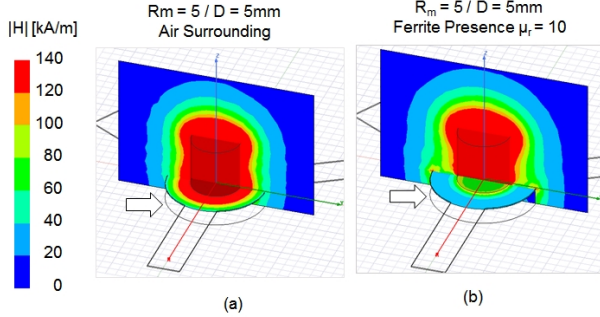


Fig. 4. Simulated magnitude of the H-Field produced by the permanent magnet (a) without ferrite (b) with the presence of ferrite puck. The relevant permanent magnet parameters are: remnant $B_r = 1.2\text{T}$, coercivity $H_c = 890\text{kA/m}$, a conductivity $\sigma = \text{S/m}$, ferrite $\mu_{\text{eff}} = 10$.

permeability μ_{eff} of the ferrite for a range of bias fields, Fig.3. Fig.4 shows an example field distribution with no ferrite and with a disk of $\mu_{\text{eff}} = 10$. A distribution for $\mu_{\text{eff}} = 2.5$ and a permanent magnet with $R_m = 3.5\text{mm}$ and $D = 2\text{mm}$ is used as input for full-wave high-frequency simulations.

III. CIRCULATOR SIMULATIONS AND PERFORMANCE

First, a microstrip circulator (Fig.1) is designed with a ferrite cylindrical puck for which the DC magnetic bias field is assumed to be uniform and above saturation. The magnetic saturation given for the Skyworks TT1-105 ferrite is $M_S = 0.175\text{T}$ [6]. Assuming a saturated ferrite, $f_0 = 3.9\text{GHz}$, $\mu_{\text{eff}} = 2.5$ and $\epsilon_r = 12.2$, the puck radius can be calculated from [1] to be $R_f = 4.49\text{mm}$. After full-wave simulations in HFSS, the final radius is set to $R_f = 4.97\text{mm}$. For $50\text{-}\Omega$ ports and with no additional impedance matching, an isolation and match of better than 20dB and an insertion loss of 1.8dB are obtained around 3.9GHz . The non-uniform field distribution in the ferrite is shown in Fig.5. This distribution is discretized with concentric circles, and within each hollow cylindrical volume, a uniform field is assumed for HFSS simulations. The resulting circulator performance is plotted in Fig.6 along with the baseline saturated design, with observed shift in frequency and increased loss and isolation. We conclude that the DC magnetic bias field nonuniformity needs to be taken into account for accurate modeling of circulators through co-simulation of the DC and high-frequency performance.

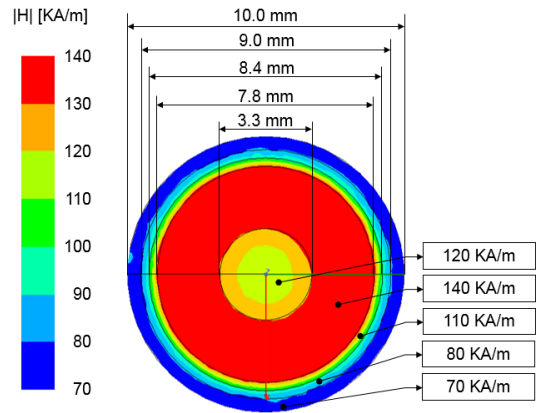


Fig. 5. Nonuniform DC B-field magnitude with discretization volumes for full-wave simulations of effects on circulator performance. Magnet dimensions $R_m = 3.5\text{mm}$, $D = 2\text{mm}$, $\mu_r \text{ferrite} = 2.5$.

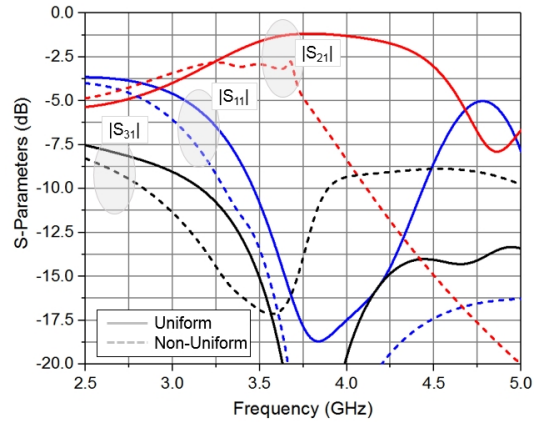


Fig. 6. Simulated S-parameters of the two circulators over frequency, showing that a nonuniform DC magnetic field from a small permanent magnet affects performance and can be taken into account by co-simulation.

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