Investigation of the Impact of Magnetic Permeability and Loss of Magnetic Composite Materials on RFID and RF Passives Miniaturization

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Abstract — **The successful implementation of a magnetic composite material has enabled the investigation of the potential impact on RFID and RF passives miniaturization, considering both material/fabrication properties and geometric design parameters. The benchmarking structure is a short-circuited quarter-wavelength rectangular patch antenna for RFID UHF band (400 – 930 MHz). The antenna is electromagnetically modeled in HFSS full wave EM (electromagnetic) software and optimized using statistical tools, and it is found that the permeability of a practical magnetic composite can enable miniaturization by a factor larger than 3, something that could be replicated for other large-size RF passives, such as integrated inductors. The impact of the magnetic loss of the composite on the miniaturized antenna performance is also evaluated. In addition, the proposed technique could provide a-priori confidence levels in the performance of RF passives and modules considering realistic fabrication variations and novel material characterization uncertainties and tolerances.**

Index Terms — **Magnetic composites, RFID, UHF, RF passives, statistical tools, hybrid optimization, fabrication tolerances, microstrip patch antenna**

I. Introduction

The inception of RFID (radio frequency identification) has enabled contactless transfer of information without the requirement of line of sight association, specifically between a reader and transponders that reside on an identified item. As the technology for RFID systems developed, there has been a need to design more flexible systems enabled at the transponder, namely miniaturization of the transponder and ability to tune system performance to accommodate EM (electromagnetic) absorption and interference from surrounding media [1]. Three-dimensional transponder antennas that utilize wound coil inductors do make use of magnetic cores, but magnetic materials for two-dimensional embedded planar antennas have not yet been successfully realized for standard use. As their three-dimensional counterparts, two-dimensional embedded antennas can reap the same benefits from magnetic materials.

One of the most significant challenges for applying new magnetic materials is understanding the interrelationships of the new materials, design, and performance. In previous studies, it can often be cited that the objectives of miniaturization and improved performance are limited by the limited availability of materials that possess the required properties [2]. Recently, formulation of nano-size ferrite particles has been reported [3] and formulation of magnetic composites comprised of ferrite filler and organic matrix has been demonstrated [4]. The implication of these new magnetic materials has not been investigated for specific EM systems. Additionally, in some cases for which an EM system is relatively complex, the codesign of the materials with the structure may be necessary in order to achieve targeted performance. The aim of this work is to provide a basis for the codesign of materials and EM structures, namely, a NiZn ferrite-silicone composite and a microstrip patch antenna, respectively.

In this study, a benchmark structure is first designed in an EM simulator with the assumptions for an unfilled silicone substrate, followed by physical realizing and testing the structure to ensure agreement with simulation. Then, the EM simulator results, which assume material property variables of a magnetic composite and geometric design variables, are incorporated into the Design of Experiments (DOE) and Response Surface Method (RSM) statistical optimization techniques, which give a thorough understanding of the system and, most importantly, give information such as how the electrical performance is affected and how they could enhance the capability for miniaturization. The next step was the actual fabrication of the material and the measurement of the electrical and magnetic characteristics, including loss. Finally, the electrical performance of the miniaturized antenna is predicted based on the measured properties. This methodology enables the designer to investigate a system of parameters that include material properties and design geometries for the structure simultaneously and weigh tradeoffs instantaneously, thereby developing an in-depth understanding of the implications that new materials have on design.

II. Initial Analysis

The analyzed structure was a short-circuited quarter-wavelength rectangular patch antenna for RFID UHF band (400 – 930 MHz). The overall dimensions of the microstrip patch antenna including the ground and the surrounding dielectric were 180 mm x 180 mm. The initial structure was designed for the lower end of the UHF spectrum and was modeled using HFSS full wave EM (electromagnetic) software. The initial substrate was pure silicone (ε_r = 2.65 and tanδ_μ = 0.001) of 1.6 mm thickness, and the structure showed a resonant frequency of 385 MHz for a 110mm x 110 mm short-circuited patch dimension. Then, the antenna was fabricated and the resonant frequency of 385 MHz was verified. The goal of this paper is to maintain the same dimensions of the antenna for the magnetic composite material and to show a decrease in resonant frequency with increased magnetic permeability, which proves the miniaturization concept.

In the first step of the analysis, the hybrid EM simulation/statistical tools methodology was applied to quantify the effect of material properties and geometries on the performance of the benchmarking structure. The chosen statistical tool was full factorial DOE with center points [5]. The factorial designs are used in experiments involving several factors, where the goal is the study of the joint effects of the factors on a response. The 2^k factorial design is the simplest one, with *k* factors at *2* levels each. It provides the smallest number of runs for studying *k* factors and is widely used in factor screening experiments [5].

For the DOE, the parameters under investigation as input variables were ε_r (relative permittivity), μ_r (relative permeability), and *d* (inset length). The output variables, or responses, for the DOE were f_{res} (resonant frequency) and *RL* (return loss). Several initial simulations of the system provided direction that *g* (inset gap) and *h* (substrate height) could be held constant at 20 mm and 0.2 mm, respectively, because they did not produce large changes in responses f_{res} and *RL*. Additionally, holding *g* and *h* constant enabled a substantially smaller DOE, requiring fewer simulations. Although not included in the DOE, *w* (microstip width) was simulated separately to ensure 50Ω impedance matching, depending on values for ε_r, μ_r, and *h* for the different experimental conditions. The antenna dimensions considered as possible input variables are shown in Fig. 1.

The design space for the input variables was chosen such that it includes values of an actual magnetic composite material that has been formulated and incorporates fabrication limitations and design rules for the dimensions. The ranges for the input variables for the DOE are presented in TABLE I.

TABLE I
RANGES FOR THE INPUT VARIABLES FOR DOE

Variable	Low value "-"	High value "+"	Center point
ε_r	2.5	6.5	4.5
μ_r	1	6.5	3.75
d (mm)	3	9	6

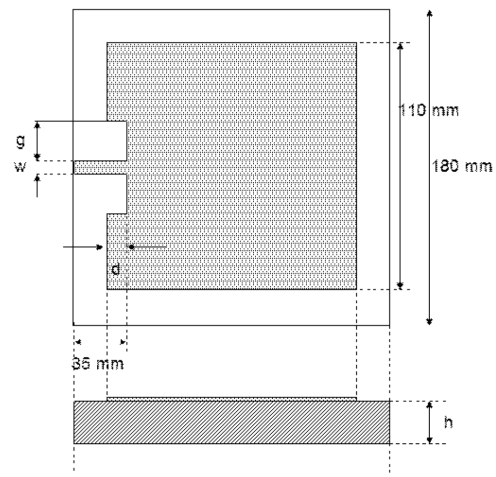

Fig. 1. Antenna dimensions

Once the responses were obtained for the experiment, the best fitting first order statistical model was determined. Next, the fit was investigated for ultimate lack of fit. An ultimate lack of fit can arise from curvature in the response or increased variation of fit at one end of the model, for example. In cases that curvature in the response is detected, the analysis may be extended to additional axial points indicated by the RSM, which can account for curvature through second order model development [5]. Usually, these second order models are reasonable approximations of the true functional relationship over relatively small regions. Once validated using statistical diagnostic tools, the models approximate the actual system within the defined design space.

In this case, the 2^3 full factorial DOE was performed for the first-order statistical models and RSM was needed for the second order statistical models. Once the models were validated for the model assumptions, the final statistical models were confirmed for prediction of the output variables. Then, actual material properties of ε' and μ' measured for a fabricated magnetic composite were applied to the model in order to determine implications on antenna performance.

III. Statistical Analysis

From the DOE, first order statistical models were developed. The first order model for f_{res} showed to have poor fit, and the first-order model for *RL* showed to have reasonable fit. Continuing with the optimization methodology, a second order model was developed using RSM to account for the detected curvature in f_{res}. The developed model included the terms ε_r, μ_r, and the interaction $\varepsilon_r * \mu_r$. The curvature was alleviated by including the second order terms ε_r^2 and μ_r^2. The model for f_{res} is given by (1). The developed statistical model for *RL* from the RSM included the term for *d* only. The model for *RL* is given by (2).

$$f_{res} = 147.8 - 26.5\left(\frac{\varepsilon_r - 4.5}{1.5}\right) - 35.0\left(\frac{\mu_r - 4.25}{1.75}\right) + 6.54\left(\frac{\varepsilon_r - 4.5}{1.5}\right)\left(\frac{\mu_r - 4.25}{1.75}\right) + 5.78\left(\frac{\varepsilon_r - 4.5}{1.5}\right)^2 + 11.38\left(\frac{\mu_r - 4.25}{1.75}\right)^2 \quad (1)$$

$$RL = -14.72 + 2.77\left(\frac{d - 6}{2}\right) \quad (2)$$

Before accepting (1) and (2) as the final models, the models had to be confirmed. The confirmations of the models were performed for the following combination of parameters: ε_r = 5.1, μ_r = 2.9, and d = 4.7 mm. This combination of input variables was simulated in the EM simulator and was also predicted with the developed models. Results of the simulation compared to the DOE 95% confidence intervals defined by the lower and upper bounds for the predicted resonant frequency f_{res} and return loss RL are shown in TABLE II.

TABLE II.
f_{res} AND RL FROM EM SIMULATION COMPARED TO DOE 95% CONFIDENCE INTERVALS

	f_{res} [MHz]	RL [dB]
Simulation	171.4	-14.5
DOE lower bound	160.2	-22.1
DOE upper bound	179.6	-11.0

Because the simulation values fall into the 95% confidence intervals, the models were confirmed. With this confirmation, the models given by (1)-(2) were accepted as the final models.

IV. Model Interpretation and Application

The final step in the study was applying measurements of a fabricated magnetic composite material to the models. The material was formulated from Dow Corning Sylgard 184 silicone and Steward NiZn ferrite powder #72599. A 40 vol% ferrite paste was produced with a mixer at 240 rpm and 110°C for 30 minutes. The paste was transferred into a flat mold and vacuum cured with a hold confirmed to occur at >125°C for 50 minutes to produce a 1.6 mm thick substrate.

The material was measured using an HP4291A impedance analyzer with material fixtures 16453A for ε_r and 16454A for μ_r over the frequency range of 1MHz to 1.8GHz. There were 5 measurements taken for each ε_r and μ_r. The summary statistics including the mean and 95% C.I. (confidence intervals) for ε_r and μ_r of this first ferrite composite at 122 MHz are given in TABLE III. Based on these results, the values used in the model were ε_r = 6.3 and μ_r = 4.3.

According to the model, RL is minimized when d is minimized. To minimize RL, d was set equal to 4. With these values for ε_r, μ_r, and d, the model predicted f_{res} = 122 MHz and RL = -17.5 dB. The surfaces of the possible solutions from the statistical models are shown in Fig. 3.

TABLE III.
MEAN AND 95% CONFIDENCE INTERVALS FOR ε' AND μ' OF FIRST FERRITE COMPOSITE AT 122 MHz

	mean	*Lower CI*	*Upper CI*
ε_r	6.332	6.227	6.437
μ_r	4.252	4.249	4.255

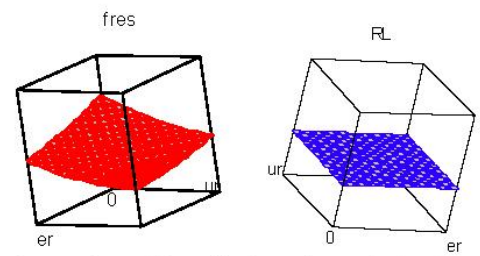

Fig. 3. Surfaces of possible solutions for optimized f_{res} and RL

Comparing substrates, the shift down in frequency from f_{res} = 385 MHz for the pure silicone substrate to 122 MHz for the magnetic composite substrate proves the miniaturization concept (by a factor 385/122~3.2). Similar benefits can be observed for other large-size RF passives, such as integrated RF inductors, that potentially play a critical role in the size of integrated RF modules.

The loss of the magnetic composite material is an important issue to be addressed. The change in f_{res} and RL with increased magnetic loss tangent for the optimal structure is presented in Fig. 4. The x-axis has a logarithmic scale, so the return loss degrades exponentially with the magnetic loss.

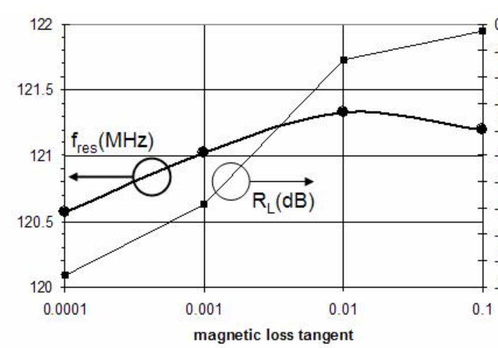

Fig. 4. Effect of loss on antenna performance.

Because of the magnetic loss of the composite described in TABLE II, a different material was formulated using another ferrite powder having relatively lower magnetic loss at the targeted operating frequencies and processed to produce a 2.5 mm thick substrate. For the initial formulation of this material, there were 5 measurements taken for ε_r, μ_r, $\tan\delta_\varepsilon$, and $\tan\delta_\mu$ over the frequency range of 1MHz to 1.8GHz. The mean for

ε_r, μ_r, tanδ_ε, and tanδ_μ of this second ferrite composite at 122 MHz are given in TABLE IV.

TABLE IV.
MEAN FOR ε_r, μ_r, tanδ_ε, AND tanδ_μ OF SECOND FERRITE COMPOSITE AT 122 MHz

	mean
ε_r	21.260
μ_r	4.282
tanδ_ε	0.204
tanδ_μ	0.0371

A patch antenna with the same overall size of 180 mm x 180 mm was simulated with HFSS EM software and preliminarily optimized for the second ferrite composite. The material properties ε_r, μ_r, tanδ_ε, and tanδ_μ were included in the simulation as a function of frequency. The resulting reflection coefficient S11 for the patch antenna showed f_{res} = 75MHz and RL = -6.5dB. The resulting reflection coefficient S11 as a function of frequency is presented in Fig 5. The miniaturization factor of better than 3 is demonstrated with this composite also. This is a very promising preliminary result and the further optimization of the antenna is in progress.

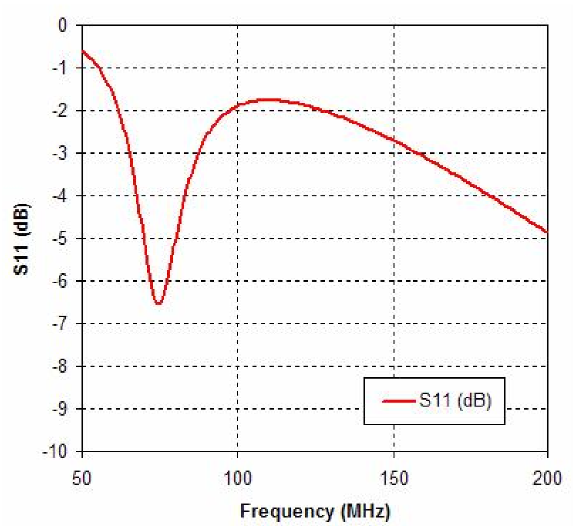

Fig. 5. Reflection coefficient S11 as a function of frequency

V. CONCLUSIONS

A combination of electromagnetic and statistical tools (DOE and RSM) has been used to investigate the impact of magnetic composite materials to the miniaturization of RFID antennas and RF passives considering geometric, material and fabrication parameters and uncertainties. This approach has been applied to the design of a benchmarking microstrip patch antenna and has enabled the assessment of implications that materials have on this design. The experiment was simple to implement and provided a thorough understanding of the issues to be confronted in the design process. A real composite material has been fabricated and the performance of the miniaturized antenna predicted using the models. Finally, the impact of the magnetic loss was assessed and integrated in the miniaturized antenna simulation. By extending this approach to carefully investigate the behavior of a complete modules and package and including additional parameters, such as the overall structure size and the material loss variation with frequency, the designer can save a lot of time, shorten the design cycle of added functions, and optimize designs in a simple and elegant manner and with a profound understanding of how all these aspects are affecting each other.

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