Inkjet-Printed Ferromagnetic Nanoparticles for Miniaturization of Flexible Printed RF Inductors

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***Abstract*—This work investigates the integration of inkjet-printed ferromagnetic nanoparticles on printed RF inductors on paper substrate to evaluate the effects of miniaturization and inductance. A cobalt-based ferromagnetic nanomaterial is printed on top of a meandered inductor on paper substrate. The effects of increased thickness of the ferromagnetic thin film are investigated as well as the effect of bending the inductor for flexible printed electronics. This flexible, miniaturized inductor can be coupled with a printed capacitor to create a fully inkjet-printed resonant LC circuit that can be mounted on the body for sensing applications such as various gases or humidity depending on the dielectric material used.**

I. INTRODUCTION

Magnetic materials have been used in the past to further miniaturize RF passives such as antennas and inductors [1]-[5]. In these works, the magnetic material was fabricated onto the passive devices by techniques such as dc magnetron sputtering [1], creating a thick paste using commercial epoxy that is applied onto the device [2], or making bulky ferrite plates on which the device is fabricated [3]. In all of these fabrication scenarios, although the inductors and antennas had improved miniaturization due to the magnetic material, the devices were rigid and bulky components, because the devices were fabricated on silicon substrate and the magnetic material was rigid and brittle.

In this work, an inkjet-printing approach to apply ferromagnetic nanomaterial is investigated to produce a truly flexible, printed RF inductor. The flexible RF inductors can be coupled with other flexible RF components such as interdigitated capacitors to create resonant LC tanks. Furthermore, flexible, miniaturized antennas and RFID tags can also be realized for bio-monitoring applications.

To investigate the feasibility of inkjet-printed ferromagnetic nanoparticles on RF inductors, several steps were taken. First, the nanomaterial was developed and optimized so that the ink would jet properly in the Dimatix materials printer that was used. Second, a meandered RF inductor was designed on paper substrate to mitigate the effect of vias due to spiral inductors. Thirdly the feed was designed for probe measurements to minimize measurement errors from sma connectors. Fourthly, the effect of various thicknesses on the percentage of miniaturization was investigated. Lastly, the effect of bending the inductors was also investigated.

II. FERROMAGNETIC NANOMATERIAL DEVELOPMENT

For first step for this work was to develop a ferromagnetic composite on a nanoscale of less 200 nm in order to jet through the Dimatix materials printer. Commercially-available fine cobalt nanoclusters synthesized from carbonyl decomposition in a non-aqueous medium and passivated with a polymer layer to protect the surface, were selected. A surface coating, AOT (Sodium Dioctylsulfosuccinate), in conjunction with the native oxide, prevents oxidation during handling. Various polymers were evaluated to make the composite less brittle and of lower loss, and fluropolymers were chosen as the candidate [6].

The material was characterized using an HP4291A impedance analyzer to obtain the complex permeability with material fixtures 16454A for μ over 200 MHz to 1000 MHz. Characterization of the permittivity properties was performed by matching the simulation data obtained from CST simulations to the measurement data at several frequency points. Based on these results, the values used in the model were $\varepsilon_r = 7.4$, $\mu_r= 2.6$, $\tan\delta_\varepsilon = 0.05$, $\tan\delta_\mu = 0.16$.

III. INDUCTOR DESIGN

The main focus on the inductor design was to investigate the effect of the ferromagnetic nanomaterial. Therefore, although a spiral inductor would give a higher inductance per area, a meandered inductor was chosen because of the lack of vias and minimal fabrication complexity which was desired to mitigate the effect of fabrication errors, in order to accurately investigate the effects of just the ferromagnetic nanomaterial. The inductors were designed in CST Microwave Studio, as shown in Fig. 1 below with the dimensions shown in Table 1 below. The inkjet-printed prototypes are also shown in Fig. 1, with and without the ferromagnetic layer. The fabricated prototype shows a greater area dimension of the thin film in order to maximize the flux through the film, whereas the simulation focused on study of film thickness versus miniaturization.

TABLE I. INDUCTOR DIMENSIONS (MILLIMETERS).

L	W	fl	fw	g	cpw
13.6	9	5.2	1.4	0.25	5

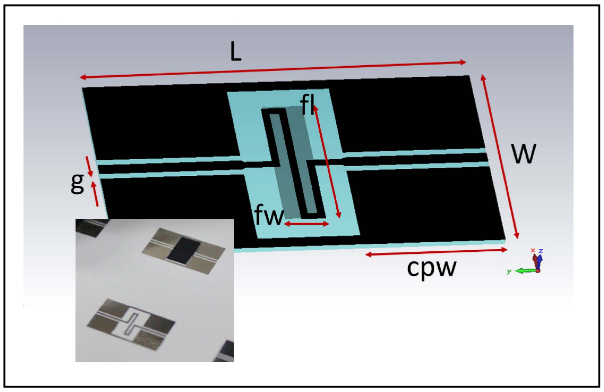

Figure 1. Design and printed prototype of inductor.

The grey area on top of the inductor is the model for the ferromagnetic thin film. Various thicknesses of 50um, 100um, and 200um of the ferromagnetic thin film has been simulated to see the miniaturization effect, as shown in Fig. 2 below.

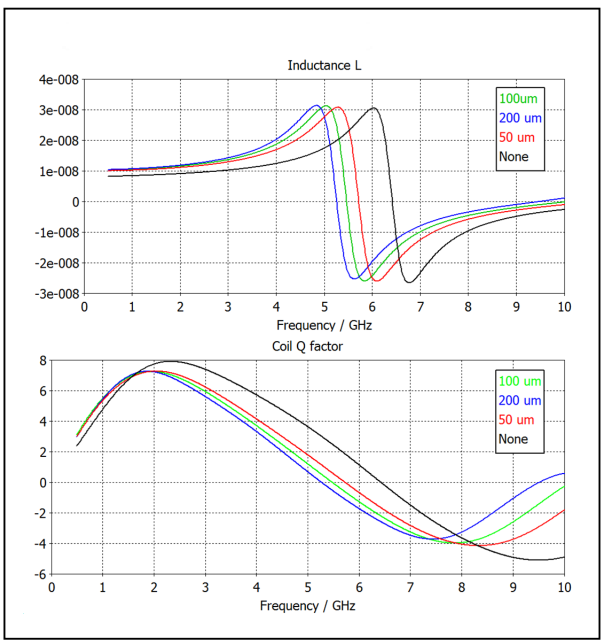

Figure 2. Miniaturiation and Q with different thicknesses of ferromagnetic thin film.

The percentage change in miniaturization is tabulated in Table II below. The Q factor shows a decrease of about 1 due to the magnetic loss tangent of the ferromagnetic thin film.

TABLE II. MINIATURIZATION.

Thickness	None	50um	100um	200um
fres	6.037	5.28	5.06	4.85
% Δ	0%	12.5%	16.2%	19.7%

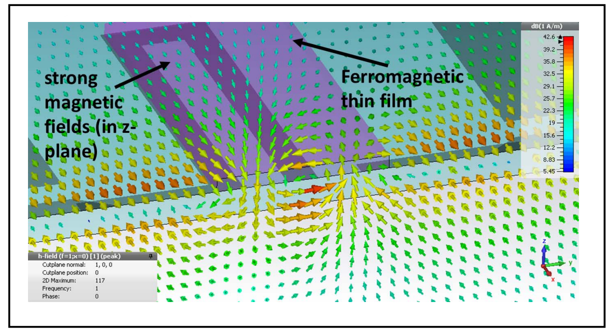

Figure 3. Magnetic fields at cross section of inductor.

To investigate the effect of a bending, the meandered inductor was wrapped around a vacuum cylinder with radius of 1mm. There was little change in inductance or quality factor, and the insertion loss showed no change at the SRF and had less than 1dB variance at 500MHz and 1.1dB at 10GHz. The magnetic fields plotted in Fig. 3 show that the flux flows through both the substrate and the ferromagnetic thin film. The field strength was higher at 42.6 dB (A/m) compared to 39.1 dB (A/m) with the thin film than without. Due to the flow of current in the meander, and the density of the flux at the corners, the strong magnetic fields exist on the z-plane inside the meander lines near the top and bottom, as indicated in Fig. 3.

IV. RESULTS AND CONCLUSION

For the miniaturization of flexible, fully printed RF inductors, ferromagnetic thin film on a meandered inductor was investigated. Increased film thickness showed increased miniaturization effects and the bending of the inductor showed a small change in the insertion loss, which allows the flexible inductors to be used in printed LC tanks for applications such as wearable RF and bio-monitoring applications.

REFERENCES

[1] B. Viala, A. S. Royet, R. Cuchet, M. Aid, P. Gaud, O. Valls, M. Ledieu, and O. Acher, "RF Planar Ferromagnetic Inductors on Silicon," IEEE Transactions on Magnetics, vol. 40, no. 4, July 2004.

[2] Markondeya Raj, P.: Prathap Muthana; Xiao, T.D.; Lixi Wan; Devarajan Balaraman; Abothu, I.R; Swapan Bhattacharya; Madhavan Swaminathan; Rao Tummala, "Magnetic nanocomposites for organic compatible miniaturized antennas and inductors," Advanced Packaging Materials: Processes, Properties, and Interfaces Proc., pp. 272-275, 2005.

[3] B.Y Liu, H.W Zhang, X.L Tang, H Su, "RF Integrated Planar Inductor Fabricated on Ferrite Substrates," Communications, Circuits, and Systems Proc., vol. 4, pp. 2623-2624, 2006.

[4] Li Yang, Lara J. Martin, Daniela Staiculescu, C. P. Wong, Manos M. Tentzeris, "Conformal Magnetic Composite RFID for Wearable RF and Bio-Monitoring Applications," IEEE Trans. On Microwave Theory and Techniques, vol. 56, no. 12, December 2008.

[5] Eyad Arabi, Atif Shamim, "High Q, miniaturized LCP-based passive components, and filter design for SoP applications," Proc. Of 41st European Microwave Conference, pp. 111-114, 2011.

[6] Raj, P.M; Shama, H.; Reddy, G.P.; Reid, D.;, Altunyurt, N.; Swaminathan, M.; Tummala, R.; Nair, V., "Novel nanomagnetic materials for Novel nanomagnetic materials for high-frequency RF applications," Electronic Components and Technology Conference, pp. 1244-1249, 2011.