Inkjet Printed High-Q RF Inductors on Paper Substrate With Ferromagnetic Nanomaterial

Hoseon Lee, Benjamin S. Cook, K. P. Murali, *Member, IEEE*, Markondeya Raj, and Manos M. Tentzeris

***Abstract*—For the first time, high quality factor (Q), meander inductors are demonstrated utilizing inkjet-printing on organic paper substrates. Quality factors of up to 25, which is an order of magnitude greater than previous works, and inductance values of up to 8 nH are achieved. The high self-resonance frequency (SRF) of 8 GHz makes it possible for the inductors to be used in the 900 MHz and 2.4 GHz RFID bands, and in 5 GHz Wifi band. Furthermore, a study into the performance and miniaturization effects of inkjet-printing ferromagnetic nanomaterial onto the inductors shows increases in inductance of up to 5%. Applications for inkjet printed inductors include all-printed flexible and wearable filters, resonators, and microwave matching networks.**

***Index Terms*—Ferromagnetic nanoparticles, inkjet printing, miniaturization, paper substrate, RF inductor, RF Passives.**

I. Introduction

PRINTED electronics have shown tremendous growth in recent years, and the demand for faster, smaller, cheaper, and more efficient printed devices is ever increasing. Inkjet printing is a technology which has demonstrated the ability to fabricate electronic components in a rapid, additive manner which can be scaled to mass production in roll-to-roll processing to meet these needs.

Recently, there has been a push for inkjet-printed RF passive components such as multi-layer capacitors and inductors to remove the requirement for mounted discrete components in printed systems [1]. Currently, only low-frequency and low Q inductors have been demonstrated in the literature. Kang *et al.* demonstrates an inkjet-printed spiral inductor, which is characterized up to 1 MHz [2]. Menicanin *et al.* introduces an inkjet-printed meander inductor on Kapton with inductances of up to 2 nH, and quality factors of up to 3.5 with a SRF of 6.865 GHz for a single loop meander inductor [3].

Inkjet printing allows for the deposition of a wide variety of materials including magnetic material which can be integrated with printed inductors to increase the inductance. Current techniques to deposit magnetic nanomaterial on printed inductors include dc magnetron sputtering, epoxy paste application, or substrate impregnation of ferromagnetic particles [4]. These techniques result in rigid and brittle components which can't be used in flexible or wearable applications. However, the ability to print ferromagnetic nanoparticles allows for thin, conformal layers of material to be deposited rapidly and at low-cost.

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H. Lee is with the Department of Electrical Engineering, Kennesaw State University, Kennesaw, GA 30144 USA (e-mail: hoseon.lee@kennesaw.edu).

B. S. Cook is with Texas Instruments, Blue Bell, PA 19422 USA.

K. P. Murali and M. Raj are with the Packaging Research Center, Georgia Institute of Technology, Atlanta, GA 30332 USA.

M. M. Tentzeris is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA.

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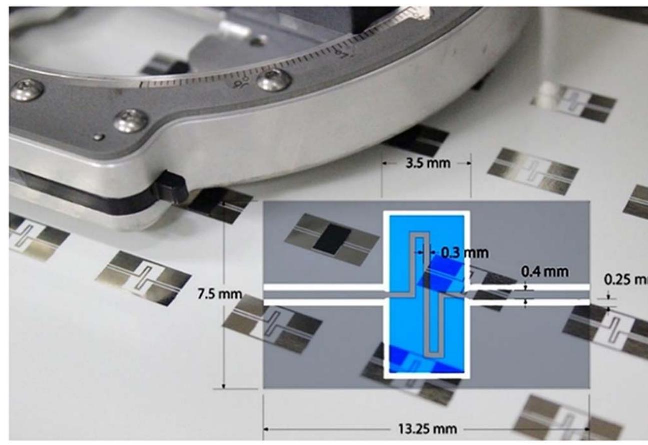
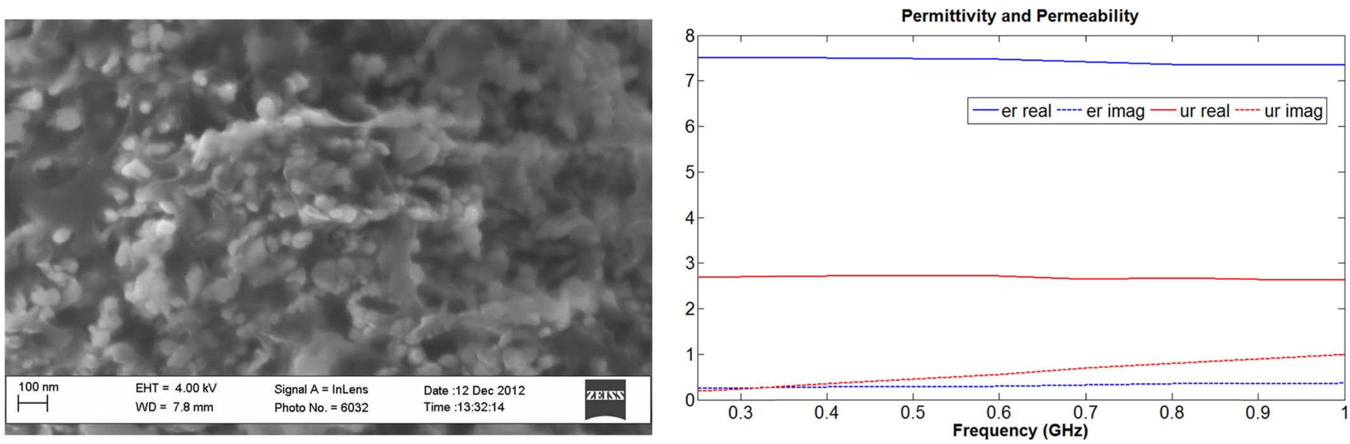


Fig. 1. Layout of fabricated inductor, and actual fabricated inductor with and without printed ferromagnetic material.

This work is based on a simulation study of an inkjet printed inductor with magnetic nanomaterial on paper substrate [5]. In this letter, the inductor is actually fabricated whereas the previous publication shows only simulation. This letter shows and demonstrates an improvement in the performance compared to previous works with inductances of up to 8 nH while maintaining a high quality factor of 25, and an SRF of 8 GHz. The inductors are integrated with printed ferromagnetic nanoparticles to investigate the high frequency performance of printed nanoparticle-based magnetic material for the first time. In this work, the RF characterization of the ferromagnetic nanomaterial for complex permittivity and permeability is first performed. The meander RF inductors are then designed and fabricated for high inductance, Q, and SRF. Measurements for the printed inductors with and without printed ferromagnetic nanomaterial are then compared with simulation.

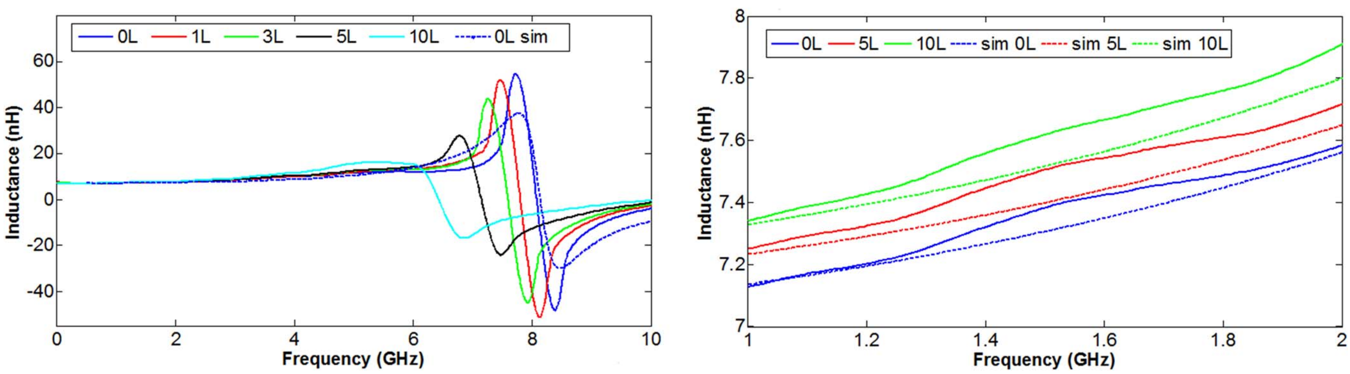
II. Preparation of Ferromagnetic Ink

The ferromagnetic nanomaterial used in this work is based on a commercially available fine cobalt nanocluster that is synthesized from carbonyl decomposition in a non-aqueous medium. The ferromagnetic nanoparticles which are less than 200 nm in diameter are coated with a thin polymer shell to prevent agglomeration when in solution and prevent oxidation. The nanoparticle ink is formulated for the Dimatix DMP 2800 series of materials printers which requires that the viscosity be near 10–12 cP and the surface tension near 30 dynes/cm^2. Fig. 1 shows the fully printed inductor on paper substrate with the



(a) (b)

Fig. 2. (a) SEM image of polymer coated cobalt nanomaterial in solution and (b) measured complex permittivity and permeability.



(a) (b)

Fig. 3. Measured (a) inductance, and (b) magnification of inductance.

printed magnetic nanoparticle ink. Fig. 2(a) shows a scanning electron microscope image of the polymer coated cobalt nanoclusters dispersed in an aqueous solution.

The polymer surface coating, AOT (Sodium Dioctylsulfosuccinate), in conjunction with the thin native oxide formed on the particles, prevents further oxidation during handling and is also demonstrated to make the printed ferromagnetic material composite less brittle and lower loss [6]. The material is characterized in [6] using an HP4291A impedance analyzer to obtain the complex permeability and permittivity from 200 MHz to 1 GHz, as shown in Fig. 1(b).

III. Inductor Design and Fabrication

Several designs for realizing printed inductors can be used such as the meander or spiral. Spiral inductors, while able to achieve a higher inductance than meander inductors, require the use of vias to connect to the inside of the spiral. Currently, inkjet-printed vias have high resistance which will drastically lower the Q of the inductors. For this reason, a CPW-based meander inductor is chosen for this work as shown in Fig. 1. A single turn was used to increase the SRF for RF applications and the width and spacing of the inductor was chosen to maximize the inductance within the limitation of the printing resolution. The inductors are designed for a commercially available photo paper substrate with a thickness 220 μm. The paper substrate has a permittivity of approximately 2.9 and a loss tangent of 0.06 below 10 GHz [7]. To fabricate the inductors, four layers of Cabot CCI-300 silver nanoparticle ink are printed onto a commercially available photo paper and then cured in an oven at 150 °C for 1 h to sinter the nanoparticles together. The ferromagnetic nano-ink, sonicated for 1 hour before printing, is then printed on top of the inductor with 1, 3, 5, and 10 layers. The inductors are then placed in a nitrogen oven at 150 °C for 1 h to cure the ferromagnetic nanoparticles. Fig. 2 shows a picture of the fabricated inductors with and without the printed ferromagnetic thin film. The area of the thin film over the inductor was maximized to maximize the increase of inductance.

IV. Inductor Measurements

Measurements are performed on a Cascade probe station. To mitigate effects from the metal ground, the inductor was placed on top of a hard foam chuck. The measured S-parameters are de-embedded using a printed TRL calibration kit which was subjected to the same processing conditions as the printed inductors. The de-embedded S-parameters are then used to extract the differential inductance and Q using equations cited in [8].

The measured inductance of the inductor topology without the ferromagnetic nanomaterial has a value 7.5 nH and SRF of 8 GHz, which matches closely with the simulation of the inductor performed in CST shown in Fig. 3. For measurements

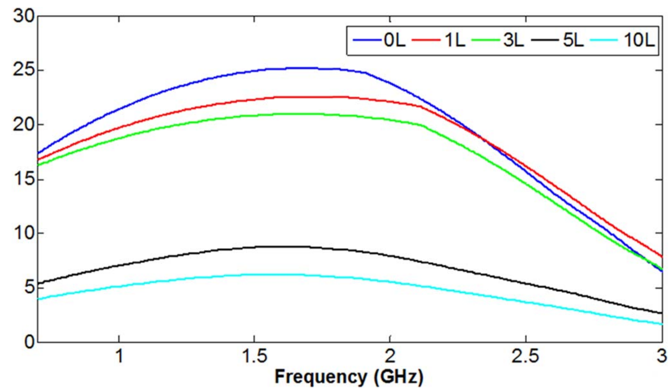


Fig. 4. Measured quality factor.

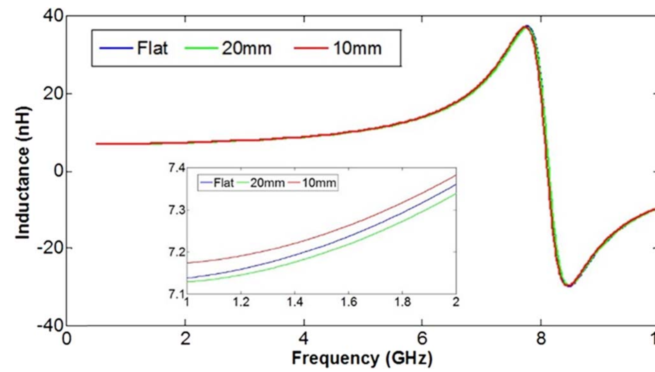


Fig. 5. Simulated inductance over a varying bending radii.

that included the ferromagnetic thin film, the high permittivity of 7.3 and the permeability of 2.6 shift the self-resonance frequency down from 8GHz to 6.44GHz. There is an added miniaturization effect due to the decrease in the wavelength by a factor of $1/\sqrt{\varepsilon_r \mu_r}$, which, in this case, equals 0.23. The smaller wavelength implies a smaller electrical length, hence the miniaturization effect compared to a substrate with a relative permittivity and permeability of 1. The high shift in SRF is caused by the added capacitance from the high permittivity of the nanomaterial as well as the increase in inductance due to the permeability. The effect of the permeability on the inductance value is shown in Fig. 3(b), in which added layers of ferromagnetic thin film increased the inductance incrementally with added layers. As a baseline, 0L stands for no added ferromagnetic nanomaterial. As the printed film is less than 5 μm thick, large inductance shifts will not occur. However, by increasing the weight percent of nanomaterial in the ink, thicker layers can be obtained which will further increase the inductance, as can also be seen in [5], which shows the simulated results of added ferromagnetic layers. The measured quality factor of the inductors shown in Fig. 4 show high quality factors of up to 25 without the printed nanomaterial. This is approximately 10 times higher than previous works for inkjet-printed components. It can be noticed that as more layers of ferromagnetic material are printed, the quality factor falls off rapidly. This is found to be caused by cracking of the silver traces when the solvent for the ferromagnetic ink is absorbed by the paper, which causes the paper to expand. Conducting dc measurements across the inductor showed resistances increasing from 2.9 to 3.1 Ω for 0, 1, and 3 layers, respectively, and from 10 to 15 Ω for 5 and 10 layers. This effect can be mitigated in future work by printing a dielectric layer over the metallization as demonstrated in [9] to hinder solvent absorption into the paper substrate. To investigate the feasibility for flexible and wearable applications, further simulations were conducted, as shown in Fig. 5, with the inductor curved around a cylinder of radii 10 and 20 mm. The inductance changed by 0.01 and 0.03 nH, the quality factor decreased by 1 and 2, and the SRF shifted by 3 and 25 MHz for radii 20 mm and 10 mm, respectively. With extensive bending of the inductor, there may be possible cracking of the ink, which can be mitigated by a sintering process as demonstrated by Jang *et al.* [10]. Since the changes to inductance, Q, and SRF are minimal, the inductor can be used in conformal applications such as inkjet-printed LC tanks for wearable biosensors.

V. Conclusion

High Q inkjet-printed inductors utilizing ferromagnetic nanomaterial are demonstrated for the first time. Maximum quality factors of 25 are obtained from measurement, which is the highest quality factor to date for inkjet-printed passives. Increased inductance with increased number of layers of ferromagnetic nanomaterial is observed which opens a path to future work in inkjet-printed component miniaturization. Further steps to increase the quality factor by insulating the metallization from the ferromagnetic ink solvent can be implemented to mitigate metallization cracking due to paper expansion. The promising results create new possibilities for inkjet-printed high-Q miniaturized flexible and wearable components operating above 5 GHz.

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