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A Magnetic Nano-Particle Ink for Tunable Microwave Applications

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***Abstract*—Inkjet printing or printing for realization of inexpensive and large area electronics has unearthed as an attractive fabrication technique. Though at present, mostly the metallic inks are printed on regular microwave substrates. In this paper, a fully printed multilayer fabrication process is demonstrated where the substrate is also realized through printing. A novel Fe_2O_3 based magnetic ink is used as a substrate while an in-house silver organo complex (SOC) ink is developed for metallic layers. Complete magnetostatic and microwave characterization of the ink is presented. At the end, a tunable patch antenna is shown as an application using the magnetic ink as the substrate. The antenna shows a tuning range of 12.5 % for a magnetic field strength of 3 kOe.**

Keywords—nano-particle ink, tunability, magnetic substrate

I. Introduction

Additive fabrication methods are gaining a lot of importance due to their low cost and ease of production. Generally fabrication techniques rely on subtraction which results in material wastage. As opposed to this, additive processes such as printing deposits material only where it is required hence reducing the material cost [1]. Moreover the roll-to-roll manufacturing capability of printing makes it a viable option for mass production in industries.

Passives such as antennas and inductors have been reported using printing for their realization [2]-[3]. Substrates such as Kapton and PEN are used to print metallic layers on them. Lately, printing of a polymer ink was shown in [4] to be used as a substrate as opposed to the usage of conventional microwave substrates. Silver ink was used for the deposition of metallic traces on the top of the polymer ink. In this paper, the authors propose the fabrication of magnetic ink to add functionality to the printed substrate which was shown in [4]. A fully printed process utilizing a custom ferrite (Fe_2O_3) based magnetic ink and a silver-organo-complex (SOC) ink for metal traces printing is demonstrated. The magnetic ink is characterized for its low frequency and high frequency properties to study its viability in tunable microwave applications. It is known that applying the magnetic fields across a ferrite material varies its magnetostatic properties, which can be used for controlling the microwave performance of a component [5], [6]. As a proof-of-concept a tunability of a patch antenna around 8 GHz is studied in this work. The results thus obtained shows that the magnetic ink is highly suitable for tunable/reconfigurable microwave devices.

II. Fabrication Process

The steps for the fabrication process are shown in Fig. 1. Due to the liquid nature of the magnetic ink, it requires a base material for its printing. For this purpose, FR-4 is used as a frame with a sacrificial paper at the bottom as shown in Fig. 1 (a). A slot (24 mm x 24 mm) is created in the FR-4 frame where the ink is deposited. Using squeegee the magnetic ink is printed inside the slot. The ink is made up of Fe_2O_3 nanoparticles with SU8 epoxy resist in 50:50 weight % ratios. Once the ink has been printed it is cured using ultraviolet rays for a period of 30 min, Fig. 1 (b). With the help of the curing the ink solidifies and can be cut through and released from the holding substrate as shown in Fig. 1(c). It is worth mentioning here that at this point the magnetic substrate still has the support paper at its back which is removed by immersing it in warm water for few minutes. The use of manual squeegee as fabrication results in a rough the surface of the substrate which needs to be smoothen out. Therefore a smoothening layer of '3D vero black plus' is printed on the top of the printed substrate. At the end, SOC ink is deposited using inkjet printing, shown in Fig. 1 (d). A total of 8 layers of SOC ink are printed and cured using infrared (IR) heating for 5 min.

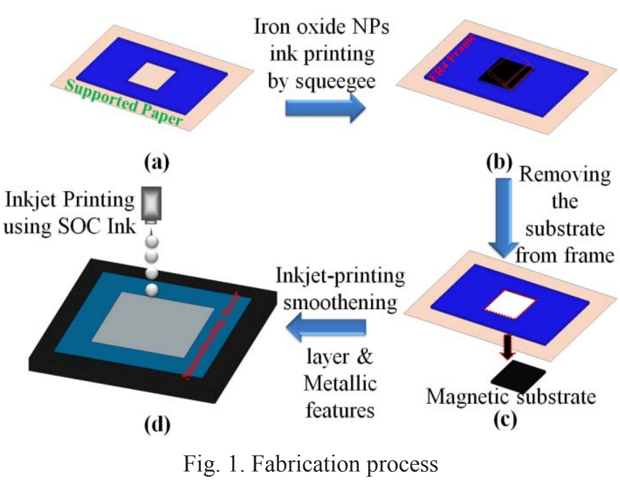


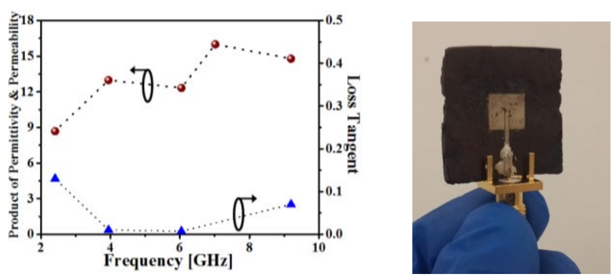
Fig. 1. Fabrication process

III. Characterization of Magnetic Ink and Antenna

A. Magnetostatic and Microwave Properties of the Fe_2O_3 Ink

To use a magnetic substrate for microwave design, it needs to be characterized for its magnetostatic and microwave properties. Therefore, the B(H) curve of the printed magnetic substrate is extracted using Vibrating Sample Magnetometer (VSM). A saturation magnetization ($4\pi M_s$), coercive field (H_c) and remanent magnetization (B_m) of 1560 G, 46 Oe and 350G respectively are obtained from the measurement. The most critical among these properties for a microwave design is the saturation magnetization which determines the magnetization frequency ($f_m = \gamma 4\pi M_s = 4.37$ GHz) of the substrate beyond which the substrate has low loss behavior.

A ring resonator is designed on the substrate for its microwave characterization. Although the resonator is measured from 0.5 GHz to 10 GHz, the properties beyond 4 GHz are of interest as explained above. Effective dielectric constant of 13, 12 and 15 are obtained at 4 GHz, 6 GHz and 8 GHz respectively. The high dielectric constant value is expected due to the ferromagnetic nature of the ink. The loss tangent value is around 0.01 which is typical for such substrates. These results are shown in Fig. 2 (a).



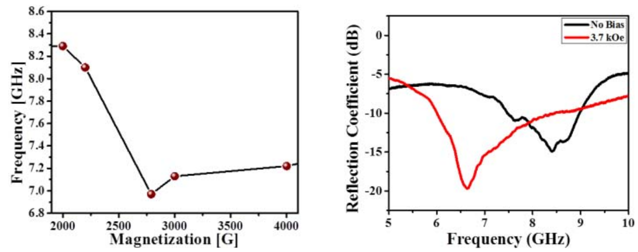
(a) (b)

Fig. 2 (a) Dielectric and magnetic properties of magnetic ink (b) Fabricated patch antenna

B. Patch Antenna Design

After the ink has been characterized for its low and high frequency properties it is now used for demonstration of an application. A linear polarized patch antenna operating at 8 GHz is used as shown in Fig. 2 (b). This frequency is selected to stay away from the low field loss region which is below 4 GHz. The antenna has dimensions of 6.4 mm × 7 mm. At first the antenna is measured for its impedance and radiation performance without any bias. A maximum gain of -0.7 dBi is achieved at 8.2 GHz. The inefficient gain value of the antenna is due to the surface roughness of the printed metal. A measured roughness value of 4.5 µm is observed from the Profilometer. Without this roughness, the gain of the antenna is around 3 dBi in simulations which is typical for ferrite based antennas. However, when the antenna is simulated with the measured metal surface roughness this value drops to -0.5 dBi. These results indicate that if the roughness of the fabricated metal can be improved, it can result in much better gain value.

The impedance and radiation properties of the antenna in the unbiased condition are acceptable for tuning measurements. To accomplish this, a magnetostatic field is applied across the antenna using an external electromagnet. The magnetic field strength is varied from 0 Oe to 5 kOe. Initially no change is observed in the center frequency of the antenna up to a bias strength of 2 kOe. As soon as the field intensity is increased beyond 2 kOe, the resonant frequency of the antenna starts to tune down as shown in Fig. 3 (a). From 2 kOe to 3 kOe the antenna shows a tuning range of 1.25 GHz. This range is almost 12.5 % of the center frequency. Further increasing the bias shows that there is a slight increase in the resonant frequency of the antenna. This can be due to the fact that the substrate is saturated for the bias field strength of 3 kOe. This means that the properties of the material are now governed by Polder's equations. The reflection coefficients of the antenna in the unbiased and biased states are shown in Fig. 3(b). No significant effect is expected on the antenna radiation pattern due to the applied bias as it has been reported previously that the radiation pattern of ferrite based patch antenna does not change much in the biased state [6].



(a) (b)

Fig. 3 (a) Measured frequency tuning (b) S_{11} measurements for no bias and 3.7 kOe bias

IV. Conclusion

Fabrication and characterization of a fully printed Fe_2O_3 based magnetic ink is presented in this paper. A simple patch antenna is designed and measured to prove the viability of the ink as a substrate for tunable microwave components. The antenna exhibits a tuning range of 12.5 % around the center frequency of 8 GHz for a magnetic field strength of 3 kOe. The functionality of the ink demonstrates that it can be used for tunable and reconfigurable microwave applications.

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