Design and Characterization of Ink-jet and Screen Printed HF RFID Antennas

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Abstract—**The physical and electrical characterization of several patterns printed by ink-jet and screen printing are presented in this work. The main goal is to determine suitable techniques to manufacture RFID antennas by using different conductive Ag inks, pastes and substrates commonly used in RFID. The physical characterization consisted of measurements of the layer thickness and the RMS roughness of the patterns. DC electrical characterization has been carried out to study different conductive inks and substrates pointing out the lowest sheet resistance and the best printability for each analyzed case. Using the optimal conditions obtained from this work, coil inductors have been fabricated by both techniques in order to validate the present study. Ink-jet printed antennas have been fabricated with Sun Tronic Ag ink on PEI substrates and screen printed antennas have been fabricated on various substrates using screen mesh densities of 90h and 140h. Finally, a semi-passive RFID tag for the HF band providing temperature and humidity sensor capabilities is presented.**

Printed electronics; ink-jet printing; screen printing; RFID; RF tag; sensor RFID

I. Introduction

Printed electronics continues to gain ground on many functional circuits and devices now possible to be fabricated by printing. Some of the pursued applications for printed electronics include radio frequency identification (RFID) tags as well as several types of wireless sensors [1]. Over the last few years, RFID automatic identification has generated a lot of interest. Conductive inks and pastes provide an alternative technology for antenna fabrication in RFID technology [2-3]. Antennas can be fabricated directly from digital format by ink-jet printing or screen printing processes implying significant R&D cost savings in antenna design and enabling high-volume production under ambient conditions using roll-to-roll techniques. Metallic nanoparticle inks typically consist of silver, copper or gold nanoparticles with diameters ranging from just 2 nm to more than 50 nm, encapsulated with a protective shell and dispersed in a liquid solvent. Once printed, a continuous conducting structure can be obtained by sintering, that is, by increasing the temperature of the structure such that the separate nanoparticles melt together. Due to the small size of the metallic nanoparticles, the sintering temperatures are significantly lower than the macroscopic melting points of the corresponding materials.

Physical and DC electrical characteristics of printed patterns determine the RF behavior of antennas and tracks for RFID applications. The diversity of commercially available conductive inks and substrates needs to be exhaustively characterized in order to gain insight about which technology would present better performance at high frequencies. Recent related works are given in references [4-8], among others, in which the importance of this analysis has been pointed out. Thus, the aim of this study is to find the techniques which present the best characteristics to manufacture RFID tags in the HF (High Frequency) band.

In this work, we have experimentally characterized the physical dimensions of patterns printed by ink-jet and screen printing, two technologies used both for prototyping and mass production. We have measured patterns with various conductive silver nanoparticle inks and substrates. This physical characterization has been correlated with DC electrical measurements of pattern conductivities. The results of the DC study are used as the basis for the design of HF antennas using electromagnetic simulation. Then, several printed coils have been fabricated by both techniques in order to characterize and compare the RF performance of the two techniques. Finally, using the manufactured HF antennas, the design and fabrication of a complete RFID tag on a flexible substrate with sensor capabilities is presented.

II. Material and Method

A. Physical and Electrical Characterization

The different substrates used in ink-jet and screen printing are Kapton HN, PET, PEI and PEN. These flexible and polymeric substrates are commonly used in printed electronics. Additionally, DCV, a polyester film used in printing applications, has also been used with the screen-printing technique for comparison. Various conductive inks made of nanoparticles of silver have been printed by ink-jet and by screen printing. Two conductive inks are used for ink-jet printing, Suntronic U5603 and Anapro DGP 40LT-15C, and one for screen printing, Sun Tronic CRSN 2442. Three different screens have been used to manufacture patterns by screen printing with mesh densities of 43, 90 and 140 Nylon threads per centimeter.

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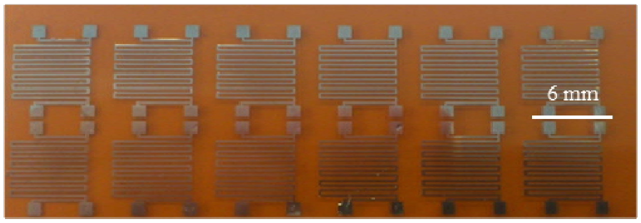

Figure 1. Ink-jet patterns.

The printed pattern by ink-jet for DC characterization consists of twelve meander-shaped devices; each of them composed of twelve parallel segments 180 µm wide separated by a gap of 400 µm, resulting in a total length of 76.36 mm. It is shown in Fig. 1. Depending on the conductive ink used, this pattern is printed with up to 13 layers with no intermediate curing between layers in order to improve alignment. A final unique curing is performed in an oven after all layers have been deposited. The DMP-2831 Dimatix printer (Fujifilm Dimatix Inc, Santa Clara, USA) has been used for the ink-jet printing. Regarding screen printing, in order to gain insight into possible variations of the resistance as a function of the printing direction, the patterns for DC characterization consist of five replicas of parallel, perpendicular and diagonal straight lines, 1 mm wide and 5 mm long. These patterns have been printed with a single layer using a Serfix III screen printing machine (Seglevint SL, Barcelona, Spain).

With respect to the physical characterization, the roughness of the substrates and printed patterns and the thickness of the patterns have been measured in three areas for each pattern with a Wyko NT1100 Optical Profiling System (VEECO, Tucson, AZ, USA). The roughness and the thickness of each pattern printed by ink-jet or screen printing are presented as the mean of the three measured values from which the associated standard deviation has also been computed as the error. RMS (Root Mean Square) error propagation has been applied when required.

DC measurements have been taken using the four-point measurement technique with an 8 1/2-bit Digital Multimeter 3158A (Agilent Tech., Santa Clara, CA, USA).

The start point to design and optimize the coil antenna has been extracted from the Wheeler model [9]. Advanced Design System (ADS) (Agilent Tech., Santa Clara, CA, USA) software has been used to simulate the inductors in order to find the proper dimensions for a specific inductance at the desired frequency. Momentum, an electromagnetic simulator that computes S-parameters for general planar circuits, including microstrip, stripline and other topologies, has been chosen as the simulation method. Momentum provides a complete toolset to predict the performance of high-frequency circuit boards, antennas, and ICs. The Svensson-Djordjevic model has been defined as dielectric loss model [10].

RF electrical characterization has been performed by measuring the inductance, quality factor and equivalent circuits of all of the manufactured inductors with different combinations of substrates and dimensions.

The measurements have been done using the four-point measurement technique with a Precision Impedance Analyzer 4294A and an impedance probe kit which provides the capability of performing in-circuit measurements (4294A1). The 4294A is an integrated solution for efficient impedance measurement and analysis of components and circuits. It covers a broad frequency range from 40 Hz to 110 MHz with basic impedance accuracy of ±0.08 %.

B. Description of the RFID tag

A block diagram of the proposed RFID tag is presented in Fig. 2. It is a microcontroller-based system designed to measure the temperature and humidity obtained from a commercial sensor. The microcontroller used for this prototype is a PIC18F46J50 (Microchip Technology Inc., USA) which has been selected because of its low power consumption (nanoWatt XLP Technology) which is ideal for battery applications.

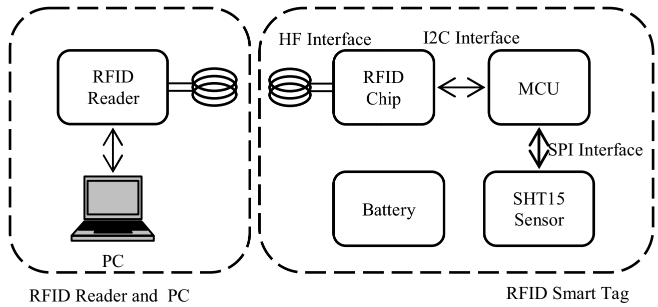

Figure 2. Block Diagram of the developed RFID tag (right) and a commercial reader (left).

The availability of I2C and SPI ports also allows easy communication with the RFID chip and the commercial sensor, respectively. A SHT15 (Sensirion AG, Staefa ZH, Switzerland) has been chosen as the sensor. This is a multi-sensor module that can be configured to measure either relative humidity with an accuracy of ±2% RH or temperature with an accuracy of ±0.5ºC. The SHT15 sensor includes a 14-bit analog to digital converter. It provides calibrated and digital data to the microcontroller via a serial interface. An M24LR64 (STMicroelectronics Inc, Geneve, Switzerland) has been selected as the RFID chip. It has a capacitance of about 30 pF at the frequency of interest, so a value of 4.6 µH must be reached to resonate without including external capacitances.

In RF mode, using the ISO15693 protocol, the RFID chip is accessed via a 13.56 MHz carrier electromagnetic wave on which incoming data are demodulated from the received amplitude modulated signal.

Apart from the RF interface, this chip works with the I2C interface which allows access to its EEPROM memory through the microcontroller. This functionality can provide sensor capabilities since it is able to interface other ICs. In this regard, it is possible to store data on the RFID chip memory that could be read out easily by a commercial RFID reader. A commercial button battery model 2032 has been used to power on the tag.

TABLE I. EXPERIMENTAL RESULTS FROM THE PHYSICAL CHARACTERIZATION OF PRINTED PATTERNS WITH DIFFERENT INKS, SUBSTRATES AND PRINTING TECHNIQUES.

Substrates	**Thickness (µm)**		**RMS Roughness**
Kapton HN	130		86,7 nm
PET	100		26,8 nm
PEI	130		22,1 nm
Patterns by ink-jet	**Layers**	**Thickness (µm)**	**RMS Roughness**
DGP / PET (160º/30 min)	2	0,36 ± 0,02	32,5 nm
	5	0,54 ± 0,07	
	7	0,72 ± 0,08	43,9 nm
	13	1,32 ± 0,02	46,0 nm
DGP / PEI (160º/30 min)	2	0,21 ± 0,01	
	5	0,56 ± 0,09	
	7	0,77 ± 0,08	
	13	1,59 ± 0,05	
Sun Tronic / Kapton HN (160º/60 min)	2	0,86 ± 0,05	63,3 nm
	3	1,30 ± 0,02	76,6 nm
	4	1,51 ± 0,03	81,2 nm
Sun Tronic / PET (160º/60 min)	2	0,71 ± 0,09	
	3	1,04 ± 0,02	
	4	1,37 ± 0,02	
Patterns by screen printing / PET	**Thickness (µm)**		**RMS Roughness**
43 T/cm Mesh	30 ± 3,0		7,75 µm
90 T/cm Mesh	19 ± 1,0		4,58 µm
140 T/cm Mesh	9,3 ± 0,2		1,61 µm

A HF band commercial reader, TRF7690_EVM (Texas Instrument Inc, Dallas, TX, USA) fully compatible with protocol ISO15693, has been used to test the RFID tag. A Visual Basic application (Microsotf Corp., Redmond, WA, USA) has been developed to configure and read out the developed RFID.

III. RESULTS AND DISCUSSION

The main results of the physical characterization of the substrates and printed patterns are summarized in Table 1 which lists the substrates, inks, number of layers and printing techniques used. The table also includes the thickness and roughness measurements, as well as the sintering conditions. The roughness measurements have been taken from an area of 250 µm x 190 µm.

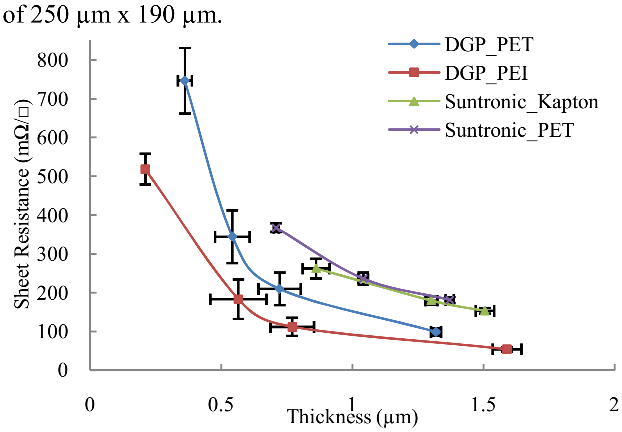

Figure 3. Sheet resistances of ink-jetted patterns as a function of thickness for different conductive inks and substrates.

TABLE II. EXPERIMENTAL RESULTS FROM THE DC CHARACTERIZATION OF PATTERNS BY SCREEN PRINTING.

Substrate	**Mesh density (T/cm)**	**Resistivity (µΩ·cm)**	**Sheet resistance (mΩ/□)**
Kapton HN	43	50 ± 2	16.6 ± 0.7
	90	44 ± 7	23.0 ± 4.0
	140	39 ± 4	42.0 ± 4.0
PET	43	46 ± 2	15.1 ± 0.7
	90	41 ± 4	21.0 ± 2.0
	140	39 ± 3	39.0 ± 3.0

In the case of ink-jet printing with the DGP ink on PET and PEI substrates, a drop-to-drop space of 50 µm has been used for 100 µm diameter (landed) drops and sintering has been done 160 ºC for 30 min. On the other hand, a drop space of 25 µm has been used for 50 µm diameter drops followed by sintering at 160 ºC for 60 min. using the Sun Tronic ink. The substrate temperature while printing has been fixed to 40 ºC.

In addition, some experimental DC measurements of resistivity and sheet resistance as a function of the thickness of ink-jet patterns have been carried out. The sheet resistances obtained for the two ink-jet printed inks on different substrates is presented in Fig. 3. Regarding the DC measurements of patterns obtained by screen printing, the results of resistivity and sheet resistance are displayed in Table 2 for two substrates and the analyzed meshes. The data are from eleven replicas and the error is given by the standard deviation. No influence of the planar orientation of the patterns has been observed. Two different HF coil inductors have been fabricated for screen and ink-jet printing, respectively. ADS simulation has been carried out to analyze and optimize both designs. Screen printed coil inductors with 6 turns and dimensions of 75 mm x 45 mm have been fabricated with a single layer. The width of the conductor and the inter-spacing between the lines are each 600 µm. An ink-jet printed coil inductor has also been fabricated using Sun Tronic silver ink on PEI substrate. The final inductor design has been manufactured with 4 layers, dimensions of 77 mm x 49 mm, 6 turns, a conductor width of 979 µm and an inter-spacing of 300 µm. This combination of substrate and ink has been chosen for ink-jet printing due to its good performance.

Although the measured sheet resistance for Sun Tronic ink is greater than the one obtained using DGP ink, the resolution is better due to the lower diameter of the deposited drops (around 50 µm for Sun Tronic versus approximately 100 µm for DGP). Furthermore, the smaller diameter reduces the required drop-to-drop spacing during printing which permits fewer layers to be used for the same final thickness. The edge profiles are also more regular in this case. The PEI substrate has been chosen owing to better printability with Sun Tronic ink than the other two substrates.

Table 3 shows the measured and simulated values of inductance and quality factor obtained by the ADS software at the frequency of interest. The data are from 4 replicas and the error is given by the standard deviation. Simulated and measured values are in good agreement in a wider range close to the 13.56 MHz operating frequency as shown in Fig.

4, 5 and 6 where it is possible to observe the frequency response of the inductors.

TABLE III. SIMULATED AND MEASURED COIL INDUCTANCE (L) AND QUALITY FACTOR (Q) AT 13.56 MHZ.

Substrate	Technique	Simulation		Measurements	
		L (µH)	*Q*	*L (µH)*	*Q*
Kapton	S.P. 90h	5.82	6.472	5.15±0.44	5.13±0.640
	S.P. 140h	6.13	2.883	5.08±0.08	2.51±0.080
PET	S.P. 90h	4.46	3.410	5.09±1.20	3.38±0.680
	S.P. 140h	4.72	2.676	5.28±0.31	2.50±0.021
PEN	S.P. 90h	4.56	3.650	4.82±0.22	3.49±0.250
	S.P. 140h	5.11	2.289	5.02±0.14	2.10±0.190
DCV	S.P. 90h	4.23	2.676	4.74±0.05	4.81±0.590
	S.P. 140h	4.26	4.862	5.10±0.17	2.40±0.270
PEI	Ink-jet	4.11	2.200	4.68	1.68

However, the self-resonance frequency is lower in the experimental measurements than in simulation. The self-resonant region is also different; it is wider in real measurements than in the simulated values. Because of this, the measured quality factors are lower than those obtained in the simulation. This tendency indicates that the real resistance is higher than the value extracted from the simulator. The process parameters of the ink-jet printing technique (deposition of drops, real dimensions, curing, side effects such as coffee ring and so on) [11-12] and the inaccuracy of the screen printed technique introduce a variability which can explain these differences.

The RFID tag prototype has been manufactured on a PET substrate. Dry adhesive film has been used to bond the chip and conductive epoxy has been used for the interconnection of each pad. The inner and outer ends of the coil have been connected through a small diameter copper wire for testing purposes. Operation of the label has been tested with a commercial RFID reader TRF7960_EVM and the developed Visual Basic application.

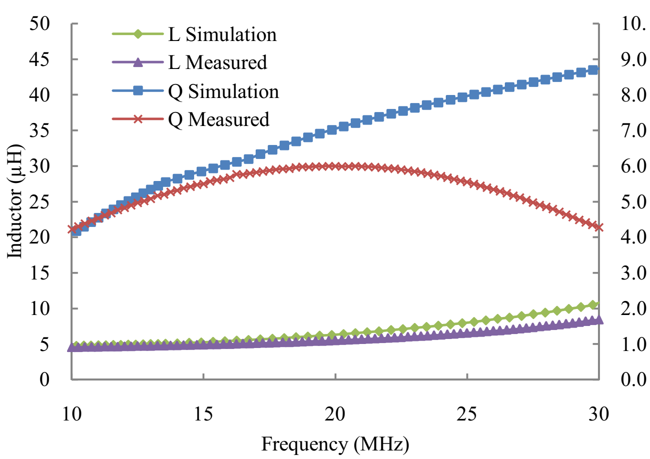

Figure 4. Experimental and simulated inductor and quality factor for screen printed inductor on Kapton with 90h mesh densities.

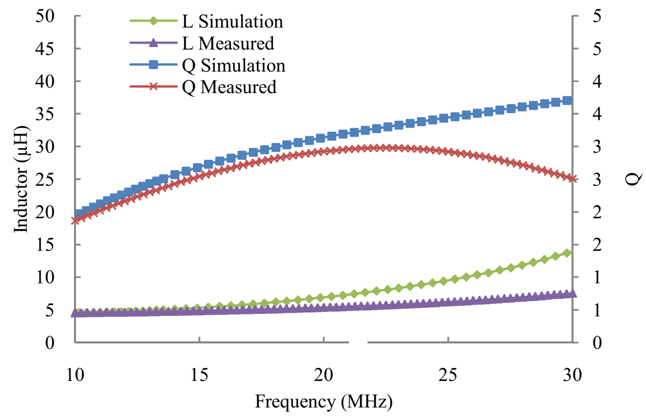

Figure 5. Experimental and simulated inductor and quality factor for screen printed inductor on Kapton with 140h mesh densities.

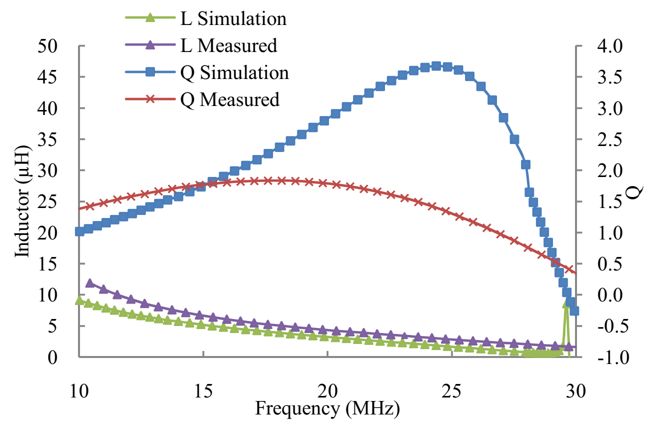

Figure 6. Experimental and simulated inductor and quality factor for ink-jet printed inductor on PEI.

Battery power is not necessary to access the data stored on the sensor making the label a semi-passive smart tag for sensing applications. Furthermore, any commercial sensor could be integrated in the design only with minor changes. Fig. 7 shows the final design of the ink-jet printed HF antenna on PEI substrate. Fig. 8 shows a screen capture of the Visual Basic application.

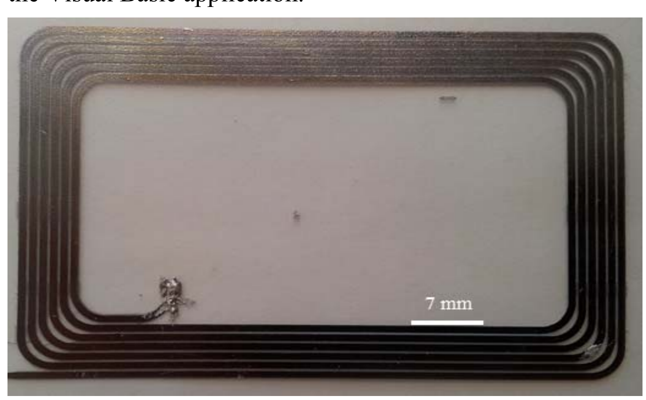

Figure 7. Ink-jet printed RF coil inductance on PEI substrate.

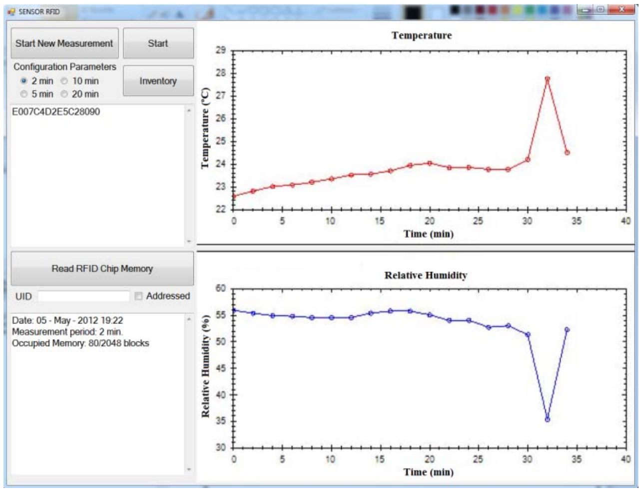

Figure 8. Visual basic application developed for TRF7960 RFID reader. data from sensor is shown on the graphs.

IV. CONCLUSIONS

This study can be summarized with the following conclusions:

- Thicker ink-jet patterns can be obtained by sequentially printing several layers with no significant degradation of the surface RMS roughness. For ink-jet printing, DGP ink on PEI has provided the best result in terms of DC conductivity compared to the other analyzed samples although the best performance in terms of resolution and thickness is provided by Sun Tronic ink on PEI substrate.
- To manufacture coil inductors using ink-jet printing, the number of printed layers must be enough to provide the required thickness in order to get a low value of resistance or, alternatively, in order not to degrade the quality factor of the RFID tag. In our particular case, 4 printed layers have been enough to fabricate an inductor using Sun Tronic ink on PEI substrate.
- Screen printing is a useful technique to manufacture inductors for RFID tags due to its low sheet resistance as demonstrated in this study. However the inductor design must take into account the irregular profiles that could be critical for inter-space gaps of planar inductors. 90h and 140h mesh densities are suitable for RF HF inductor manufacturing. The mesh density of 43 Nylon thread per centimeter has not been used for RF antenna prototyping because the required resolution to define the inductor could not be achieved.
- A semi-passive RFID tag with temperature and humidity sensing capabilities has been developed. Architecture composed of an RFID chip, an ultra-low power MCU and a commercial sensor has been fabricated on flexible substrate.

The next step is to design and develop improved HF RFID tags with smaller IC packages and better area optimization. We will also start with the design and manufacturing of UHF antennas for the European band of 868 MHz. As in the case of the HF band, we plan to study the inclusion of sensor capabilities in UHF tags with different strategies.

ACKNOWLEDGMENT

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