Inkjet-Printed RFIDs for Wireless Sensing and Anti-counterfeiting

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Abstract— **Remote Frequency identification (RFID) enables both the realization of very low-cost integration platforms with multifunctional capabilities and the implementation of low-power wireless communications. Common photo paper is investigated in this paper as the first "green" ultra-low-cost organic substrate, on which the RFID tag circuitry and antenna are inkjet-printed with conductive silver nano-particle ink. Fully integrated, RFID-enabled modules on paper are demonstrated for a wide range of wireless sensing and anti-counterfeiting applications. These paper-based devices could potentially set the foundation for the truly convergent wireless sensor ad-hoc networks of the future.**

Keywords-component; RFID; paper; silver inkjet printing; sensor

I. Introduction

The demand for low cost, robust, flexible, reliable, low-power and durable wireless modules such as RFID-enabled sensor nodes is accentuated by numerous applications, for which ubiquitous sensing and networking is a core feature. In general, RFIDs allow both the realization of very low-cost integration platform with multifunctional capabilities and the implementation of low-power wireless communications.

Paper is the first "green" ultra-low-cost organic substrate examined, on which the RFID tag circuitry and antenna are inkjet-printed. The high demand and the mass production of paper make it the cheapest and most available material ever made. From a manufacturing point of view, paper is well suited for reel-to-reel processing and has a low surface profile that makes it suitable for fast printing processes, such as direct write methodologies instead of the traditional metal etching techniques. After the silver nano-particle droplet is driven through the nozzle, it is necessary to follow by the sintering process in order to remove excess solvent and to remove material impurities from the depositions. Another benefit provided by the sintering process is the increase in the bond of the deposition with the paper substrate. The conductivity of the conductive ink varies from 0.4~2.5x107 Siemens/m depending on the curing temperature and duration time. The paper's high biodegradability, with respect to other ceramic substrates such as FR-4, allows it to turn into organic matter in landfills in only a few months and renders it one of the most environmentally friendly materials.

The knowledge of the dielectric properties such as dielectric constant (ε_r) and loss tangent ($\tan\delta$) become necessary for the design of any high frequency structure such as RFID antennas on the paper substrate. Precise methods for high-frequency dielectric characterization include microstrip ring resonators, parallel plate resonators, and cavity resonators have been used for up to 2.4 GHz [1] and lately up to 15 GHz, it making it possible to start developing 2D and 3D sensing modules encompassing wide frequency ranges.

II. RFID-Enabled Sensor on Paper

The presented RFID-enabled wireless sensor module prototype that uses a U-shaped dipole antenna was printed on a 2D single photo-paper layer [4]. The antenna and the circuit layout were printed and cured on paper using silver ink. The overall dimensions of the structure, shown in Fig. 1, are 9.5 x 6 cm. The range is above 300m and the temperature accuracy is better than 0.2C. To ensure maximum conductivity and antenna efficiency, the entire circuit was printed over with 12 layers of silver ink resulting in a conductor thickness of 12 microns.

The complete wireless sensor system comprising the TSSOP packaged integrated circuit (IC), including the MCU and the transmitter, its discrete passive components including a crystal oscillator, the TC1047 temperature sensor, and a Li-ion cell for "stand-alone" autonomous operation were assembled on the inkjet-printed metallic traces. Soldering could not be used due the low temperature tolerance of paper, the electronic

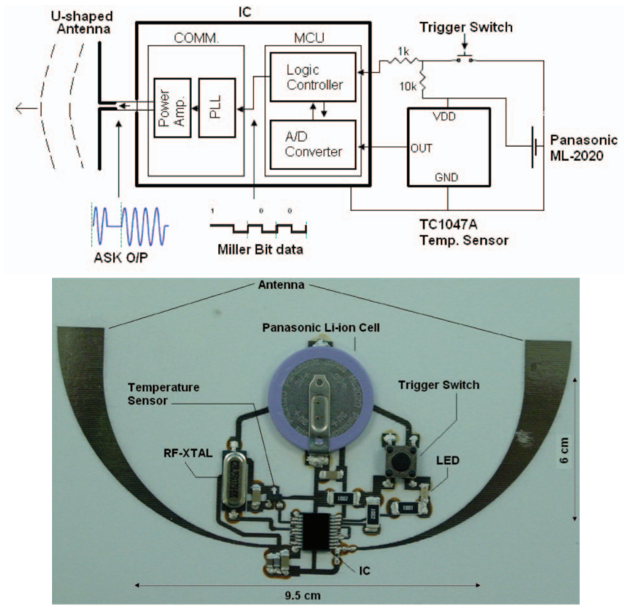

Figure 1 (a) System level diagram of the wireless sensor module, (b) RFID-enabled wireless sensor transmitter using inkjet-printing on paper

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components used, and the relative weaker adhesion of printed silver pads on paper. Multiple assembly methods were experimented in order to find a reliable alternative for mounting components, which include silver epoxies and conductive tapes. The conductivity of the silver epoxy has a direct relation to its curing time and temperature, which contradicts with the limited temperature tolerance of the components used in the wireless transmitter. Extending to a 3D multilayer paper-on-paper RFID/Sensor module is possible by laminating photo-paper sheets.

III. CONCEALABLE, PAPER-PRINTED ANTENNAS FOR WISP-BASED RFIDS

Paper-based, inkjet-printed antennas have been proposed in [2] as replacement for the conventional non-conformal, long and straight dipole antenna mounted on the WISP RFID tags [4]. One of the critical factors for the ubiquitous applicability of RFID technology is for the antenna to be as concealable, conformal, miniaturized and, thus, as unobtrusive as possible. Of course, the type of the antenna design is very significant in our effort to realize an object that can be integrated in a nonintrusive, concealable way within another object, such as the product label or a food package.

The design shown in Fig. 2 exploits meandered techniques in order to achieve significantly reduced dimensions. In particularly, text-based meandered line techniques are applied to obtain both decreased size and concealment. The photo paper has been chosen as the substrate that suits the aim of concealment for the final sensing devices. The antenna is mounted, as seen in Fig. 2, on the WISP by first soldering two short conductive wires to the board's antenna output and afterwards sticking these wires on the paper antenna with conductive epoxy, used instead of traditional soldering on heat sensitive components.

Among others, this effort has shown that inkjet printing techniques perfectly match the text-based design proposed in terms of high applicability. A comparison with the normal antennas mounted on the WISP is included in [2].

Figure 2 Inkjet-printed antenna mounted on the WISP.

IV. PAPER-BASED RFID CERTIFICATES OF AUTHENTICITY

Traditional RFIDs with encoded digital information have not been able to solve the problem of counterfeiting, which accounts for a huge financial and even life-threatening impact. Rather hardware-based approaches need to be implemented. The fundamental idea behind the proposed solution in [3] is to complement an type of RFID tag with an inexpensive physical object that physically unique and hard to near-exactly replicate and behaves as a certificate of authenticity in a unique way in the near electromagnetic field.

Each RFID-CoA instance is associated with an object, whose authenticity the issuer wants to vouch. Essentially it is a random constellation of small, randomly 3-D-shaped conductive and/or dielectric objects that exhibits a distinct behavior in its near field when exposed to RF waves over a particular frequency spectrum, namely from 5 to 6 GHz. This enables, on one hand, the extraction of the data about the product in the far field and, on the other hand, the verification of its authenticity within its near field with a virtually impossible false alarm [3]. For the first generation of physical RFID-CoA objects, we relied upon inkjet printing technique (on paper substrate), as a means of a very fast, low-cost, and in-house process. The final 3-D structure, shown in Fig. 3b can be created by tightly stacking multiple 2-D CoAs, shown in Fig. 3a, one on top of each other.

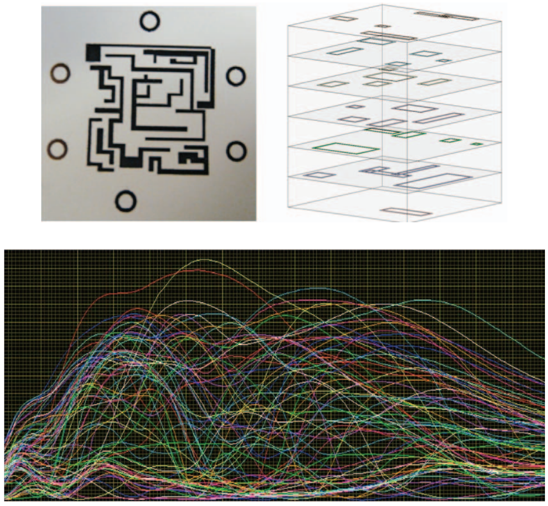

Figure 3 a) Inkjet-printed, single layer NF-CoA of rhombic loops on paper substrate. b) 3D-stacked NF-CoAs of rhombic loops. c) The near-field signature as extracted by our protoype reader for all its 72 different antenna element permutations

V. CONCLUSIONS

In this paper, inkjet-printed flexible antennas, RF electronics and sensors fabricated and assembled on paper substrates are introduced as a system-level solution for ultra-low-cost mass production of UHF RFID tags with an approach that could be easily extended to other microwave and wireless applications. State-of-the-art fully integrated wireless sensor modules on paper have been demonstrated, that could potentially set the foundation for the truly convergent wireless sensor ad-hoc networks of the future.

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