Inkjet-Printed Paper-Based RFID and Nanotechnology-based Ultrasensitive Sensors: The “Green” Ultimate Solution for an ever improving Life Quality and Safety?

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Abstract- **This article demonstrates how inkjet-printing of antennas/matching networks on low-cost paper-based materials can tackle all four challenges enabling the easy implementation of ubiquitous RFID and WSN networks by reviewing major milestones achieved in this area by this research group. It starts by discussing why paper should be used as a substrate for UHF/wireless inlays, followed by the dielectric characterization of paper using a microstrip ring resonator method. This paper then shows show how we can use conductive inkjet-printing technology for the fast fabrication of RF/wireless circuits, provides a design guideline for an inkjet-printed broadband antenna for UHF RFID tags which can be used globally, and eventually shows the capability of integrating sensors with RFID tags stressing how this functionality could revolutionize data fusion and real-time environmental cognition**.

***Index Terms* — RFID, Biosensors, Multi-hopping, Magnetic composites, CNT, gas sensors, liquid antennas, wearable applications, miniaturization.**

I. RFID AND SENSORS

The explosive growth of the biosensors and health-related wearable monitoring devices has accentuated the need for miniaturized, high-efficiency conformal materials that can operate over a wide range of frequencies, while they can be integrated in wearable and lightweight configurations. One of the major issue for the implementation of Wireless Body Area Networks (WBAN) is the very limited range of commonly used metal antennas. Due to the high dielectric constant between the metal antenna material (as well as the metal-based circuitry) and the mostly “ionized-water” human body parts, the near-field gets significantly disturbed, while local reflections due to the dielectric mismatch further shorten the operation range. Even wearable bracelet-like sensing devices have a very low range due to this reason. RFID is an emerging compact wireless technology for the identification of objects, and is considered as an eminent candidate for the realization of a completely ubiquitous “ad-hoc” wireless networks. RFID utilizes electromagnetic waves for transmitting and receiving information stored in a tag or transponder to/from a reader. This technology has several benefits over the conventional ways of identification, such as higher read range, faster data transfer, the ability of RFID tags to be embedded within objects, no requirement of line of sight, and the ability to read a massive amount of tags simultaneously [1]. A listing of applications that currently use RFID are: retail supply chain, military supply chain, pharmaceutical tracking and management, access control, sensing and metering application, parcel and document tracking, automatic payment solutions, asset tracking, real time location systems (RTLS), automatic vehicle identification, and livestock or pet tracking.

The demand for flexible RFID tags has recently increased tremendously due to the requirements of automatic identification/tracking/monitoring in the various areas listed above. Compared with the lower frequency tags (LF and HF bands) already suffering from limited read range (1-2 feet), RFID tags in UHF band see the widest use due to their higher read range (over 10 feet) and higher data transfer rate [2]. The major challenges that could potentially hinder RFID practical implementation are: 1) Cost; in order for RFID technology to realize a completely ubiquitous network, the cost of the RFID tags have to be extremely inexpensive in order to be realized in mass production amounts 2) Reliability; and that extends to primarily the efficiency of the RFID tag antennas, readers, and the middleware deployed, 3) Regulatory Situation; meaning tags have to abide to a certain global regulatory set of requirements, such as the bandwidth allocations of the Gen2 Protocols defined by the EPC Global regulatory unit [3] and [4]) Environmentally-friendly materials, in order to allow for the easy disposal of a massive number (in the billions) of RFID’s.

This article demonstrates how inkjet-printing of antennas/matching networks on low-cost paper-based materials can tackle all four challenges enabling the easy implementation of ubiquitous RFID and wireless biosensing networks. It starts by discussing how we can use conductive inkjet-printing technology for the fast fabrication of RF/wireless circuits, introduces a flexible wearable magnetic material, and eventually shows the capability of integrating sensors with RFID tags and discusses how added this functionality could revolutionize data fusion and real-time environmental cognition.

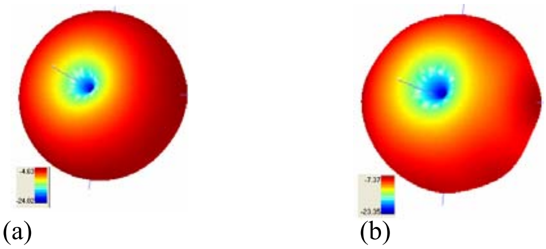
II. INKJET-PRINTING

A fast process, like inkjet printing, can be used efficiently to print electronics on/in organic substrates. This also enables components such as: antennas, IC, memory, batteries and/or sensors to be easily embedded in/on organic modules. Modern inkjet printers operate by propelling tiny droplets of liquid down to several pL. This new technology of inkjet printing utilizing conductive paste may rapidly fabricate prototype circuits without iterations in photolithographic mask design or traditional etching techniques, that have been widely used in industry. Printing is completely controlled from the designer's computer and does not require a clean room environment. A droplet's volume determines the resolution of the printer, for e.g. a droplet of 10 pL gives ~ 25μm minimum thickness or gap size of printed traces/lines. The cartridge consists of a Piezo-driven jetting device with integrated reservoir and heater.

Inkjet Printing; unlike etching which is a subtractive method by removing unwanted metal from the substrate surface, jets the single ink droplet from the nozzle to the desired position, therefore, no waste is created, resulting in an economical fabrication solution. Silver nano-particle inks are usually selected in the inkjet-printing process to ensure a good metal conductivity. After the silver nano-particle droplet is driven through the nozzle, sintering process is found to be necessary to remove excess solvent and to remove material impurities from the depositions. Sintering process also provides the secondary benefit of increasing the bond of the deposition with the paper substrate [5]. The conductivity of the conductive ink varies from $0.4{\sim}2.5\text{x}10^7$ Siemens/m depending on the curing temperature and duration time. At lower curing temperature, larger gaps exist between the particles, resulting in a poor connection. When the temperature is increased, the particles begin to expand and gaps start to diminish. That guarantees a virtually continuous metal conductor, providing a good percolation channel for the conduction electrons to flow. To ensure the conductivity performance of microwave circuits, such as RFID modules, curing temperatures around 120oC and duration time of two hours were chosen in the following fabrication to sufficiently cure the nano-particle ink. Alternatively, much shorter UV heating approaches can achieve similar results.

III. CONFORMAL PERFORMANCE

In order to verify the performance of the conformal RFID antenna, measurements were performed by conforming the same RFID tag onto a foam cylinder. The radius of the cylinder was chosen to be very small at 27mm, in order to explore the limits of the design. The return loss of the fabricated antenna is shifted down by 22 MHz with a center frequency at 458 MHz. Previous results showed a shift of 6 MHz for a lower curvature of 54mm radius, which proves that the shift is increasing with the curvature level. Overall the antenna still has good performance if the shift in frequency is considered at the beginning of the design process, even for such a large bend. Fig. 1 shows the radiation patterns for the straight and conformal antennas. The doughnut shape is slightly degraded for the conformal antenna and the maximum gain drops from -4.63 to -7.37 dBi.



(a) (b)

Fig. 1. Measured radiation pattern of (a) the flat RFID tag and (b) the conformal RFID tag. Max gain drops from -4.63 to -7.37 dBi.

The flexible nature of the substrate enables the RFID tag module's application in diverse areas. Fig. 2 demonstrates the conformal RFID tag prototype in the applications of wireless health monitoring and pharmaceutical drug bottle tracking [6].

Fig. 2. Embodiments of the conformal RFID tag prototype in the applications of wireless health monitoring and pharmaceutical drug bottle tracking.

IV. INKJET-PRINTED SWCNT GAS SENSOR

One of the major challenges of "green" paper-based RFID-enabled sensors is the integration of the sensor and nanostructures on the paper substrate as well. The application of interest for the presented work is wireless sensing of toxic gas. Carbon Nanotubes (CNT) composites were found to have electrical conductance highly sensitive to extremely small quantities of gases, such as ammonia (NH_3) and nitrogen oxide (NO_x), etc. at room temperatures with a very fast response time [7]. The conductance change can be explained by the charge transfer of reactive gas molecules with semiconducting CNTs [8]. Previous efforts have shown the successful utilization of CNT-based sensors employing the change in resistance [9]. However, due to the insufficient molecular network formation among the inkjet-printed CNT particles at micro-scale, instabilities were observed in both the resistance and, especially, the reactance dependence on frequency above several MHz, which limits the CNT application in only DC or LF band [10]. To enable the CNT-enabled sensor to be integrated with RFID antenna at UHF band, a special recipe needs to be developed.

This section presents a conformal CNT-based RFID-enable sensor node for gas sensing applications, fully printed directly on paper substrate [11]. Specifically, in this study one benchmarking RFID tag was designed for the European UHF RFID band centering at 868 MHz. The printed CNT particles were Single-Walled Carbon Nanotubes (SWCNT) from Carbon Solutions, which were dispersed in dimethylformamide (DMF) solution and sonicated to meet the viscosity requirement for the inkjet printer. The SWCNT composite is printed directly on the same paper as the antenna, for a low cost, flexible, highly integrated module. The impedance of the SWCNT film forms the sensor part. The antenna was printed first, followed by the 25 layers of the dispersed SWCNT as a load with "gas-controlled" value. When 4% consistency ammonia was imported into the gas chamber, the SWCNT impedance changed from 51.6-j6.1Ω to 97.1-j18.8Ω at 868MHz, resulting in a 10.8dBi variation in the backscattered power from the RFID antenna, that can be easily detected by the RFID reader to realize the "real-time" gas detection.As a direct-write technology, inkjet printing transfers the pattern directly to the substrate. Due to its capability of jetting one single ink droplet in the amount as low as 1 pl, it has widely drawn attention from the industrial world as a more accurate and economic fabrication method than the traditional lithography method.

CNT composites have been found to have a very unique resistance performance that can enable the realization of the next generation of sensors with a very high sensitivity up to 1ppb (part per billion), an improvement of 2-3 orders to traditional sensors. The electrical resistance of the fabricated device was measured by probing the end tips of the two electrodes. The resistance goes down from when the number of SWCNT layers increases. Since a high number of SWCNT overwritten layers will also help the nano particle network formation, 25-layer film is expected to have the most stable impedance-frequency response and selected for the gas measurement. In the experiment, 4% consistency ammonia was guided into the gas flowing chamber, which includes gas inlet, outlet and exhaust hood. The SWCNT film was kept in the chamber for 30 minutes. A network vector analyzer (Rohde&Schwarz ZVA8) was used to characterize the SWCNT film electrical performance at UHF band before and after the gas flowing. In Fig. 3, the gas sensor of SWCNT composite shows a very stable impedance response up to 1GHz, which verifies the effectiveness of the developed SWCNT solvent recipe. At 868MHz, the sensor exhibits a resistance of 51.6Ω and a reactance of -6.1Ω in air. After meeting ammonia, the resistance was increased to 97.1Ω and reactance was shifted to -18.8Ω.

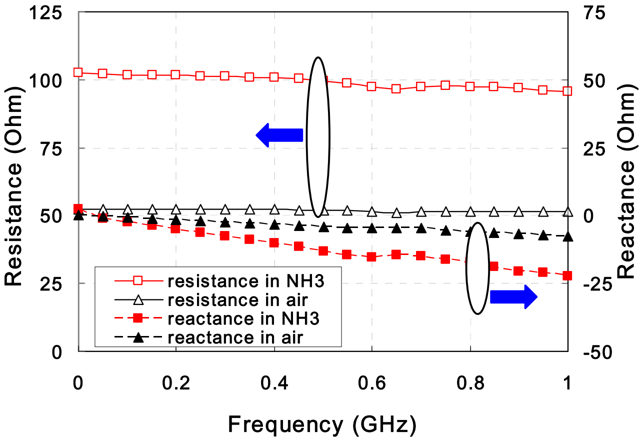


Fig. 4. Measured electrical resistance of SWCNT gas sensors.

Fig. 5. Photograph of the paper-based conformal tag.

The CNT-film was inkjet-printed a gas-sensitive load for a bow-time antenna designed to operate for RFID tags around 868MHz. (Figs.5) [11]. In the air, the SWCNT film exhibited an impedance of 51.6-j6.1Ω, which results in a low power reflection at -18.4dB. When NH_3 is present, SWCNT film's impedance was shifted to 97.1-j18.8Ω. The mismatch at the antenna port increased the power reflection to -7.6dB, a 10.8dBi increase at the received backscattered power level. By detecting this backscattered signal difference on the reader's side, the sensing function can be fulfilled.

V. LIQUID ANTENNAS FOR WEARABLE SENSORS

Metallic antennas do not operate sufficiently when planted extremely close to the human body due to the dielectric discontinuity against human tissue (Metal: ε_r=1, Blood: ε_r=58, Skin:ε_r=37), that causes the disruption of their near field. The problem of matching 'human tissue' to 'air' is commonly encountered in ultrasound techniques, which led to the research and development of tissue mimicking dielectric phantom models. In addition to matching, metallic antennas are heavy, vulnerable to corrosion, toxic to the human body and bending them introduces unwanted resonances. Liquid Antennas on the other hand, enclosed in glass would possess the biocompatible properties that would be useful for health monitoring devices, especially when they are implanted into human tissue. Plus, liquid (e.g.aquatic) solutions can be enclosed in flexible plastic, and bent in various configurations without introducing holes or air gaps, thus allowing them to operate sufficiently while worn as clothes. Liquid antennas would also be smaller as well as lighter allowing them to be easily integrated into everyday mobile human activities [12].

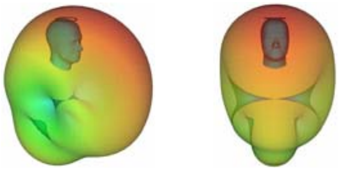


Fig.6 Liquid Antenna on "SEP" Human Phantom (NaCl ε_r=40, tan δ = 0.175 @ 915 MHz).

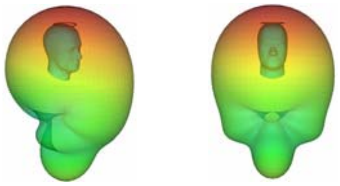


Fig.7 Metallic antenna on "SEP" Human Phantom (PEC ε_r=1).

VI. CONCLUSIONS

RFID is an emerging compact wireless technology for the identification of objects, and is considered as an eminent candidate for the realization of a completely ubiquitous "ad-hoc" wireless networks. This technology has several benefits over the conventional ways of identification, such as higher read range, faster data transfer, the ability of RFID tags to be embedded within objects, no requirement of line of sight, and the ability to read a massive amount of tags simultaneously. The effective integration of RFID's in biosensors on flexible platforms (e.g. LCP and other biocompatible organics) would allow a very effective realization of Body-Area-Networks (BAN) fully linking both wearable and implantable devices. With this real-time cognition of the status of a certain object will be made possible by a simple function of a sensor integrated in the RFID tag. The ultimate goal is to create a secured "intelligent network of RFID-enabled sensors."

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