Green Technologies and RFID: Present and Future

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***Abstract*─** RFID systems are proliferating in everyday applications. In this paper, the authors present a unified approach that relies on the development of novel low-cost inkjet-printed platforms with optimized metallization trace and effective integration of diodes for enhanced-discrimination capability applications. Potentially, the presented approach could set the foundation for the first generation of truly "green" RFID-based devices.

***Index Terms*─** UHF RFID's, inkjet-printed electronics, antennas, diode integration, multiplier.

I. INTRODUCTION

Historically speaking, the introduction of RFID took place in the defense area; it can be dated back to the 40's and ascribed to the Identification Friend or Foe (IFF) associated to the radar systems. The first scientific contribution mentioning RFID approach is probably due to Stockman [1] where information transfer via reflected waves is theorized. First commercial applications of RFID approach are testified by several patents the first of which can be likely considered by Harris [2]. RFID's were first used in anti theft systems and automatic opening systems (electronic keys). In the late 70's RFID accessed the application that would have been the leading one for many years: logistics. Still in the defense area, it was in this field that the intrinsic capability of an RFID system to give information on demand was exploited in the monitoring movements of items. At the beginning it was the monitoring of sensitive materials such as nuclear elements and weapons; afterwards, RFID monitoring accessed the civil world in the early 80's when it was first used to monitor cows, and in particular, to control their health and recovery status. In the late 80's both in Europe (Italy) and in the US (Oklahoma) automatic pay toll systems appeared, clearly theorized in open literature by Hauslen in 1977 [3], based on a gate reader and a car tag. In the early 90's, due to a collaboration between IBM and Wal-Mart, massive goods' monitoring systems based on passive, very low cost tags were implemented, constituting the first truly consumer application of RFID's, thanks to the technology improvement and the related cost reduction that allowed the realization of tags, the cost of which was in the same order of magnitude of paper labels. Potential substitution of barcodes with RFID tags, still more expensive but much more flexible and powerful, became cost-effective and RFID entered the supply chains. Since that time, the commercial deployment of RFID applications has proliferated tremendously, including, among others: vehicle and container tracking, automated toll (parking, highway, etc.), access control (also for animals), electronic doorlock, ski-lift toll, triage patient management, laundry cycle tracking, library material tracking, sport timing, etc.

In terms of regulations, in the 90's the following bands became available for RFID's: low frequency (between 125 to 134 KHz), high frequency (13.56 MHz), UHF (868 to 956 MHz), and microwave (2.45 GHz). Recently the 5.9 GHz band was also freed by the FCC.

II. PRESENT AND FUTURE TRENDS

The key trend that will drive modern societies and technologies in the next decades is strongly related to cognitive intelligence and ubiquitous ad-hoc networks in a variety of applications, such as logistics, Aero-ID, anti-counterfeiting, supply-chain monitoring, space, healthcare, pharmaceutical, and military [4]. Mobility, environment, health, security and energy will be the major technology drivers of the future, further increasing the demand for low cost, robust, flexible, reliable, low power consumption and durable wireless modules and electronics.

Addressing this major goal, electronics research, and consequently RFID, moves towards the development of flexible devices based on organic/inorganic materials and substrates attempting to overcome the limitations of ceramics and silicon. Thin, light-weight, heterogeneous, flexible and environmentally friendly, combinations of new materials and cost-effective, large area production processes are the challenges that need to be tackled for the applications of the future. Current research and manufacturing incorporates a wide range of electrical components that can be produced and directly integrated in low cost reel-to-reel processes, mainly involving organic electronics with the examination of several electrically conductive and semi-conducting materials.

Organic materials can be printed and patterned using various techniques (like flexo, gravure, offset, screen, and inject.) [5,6,7], each one with its own advantages and disadvantages. Based on these materials and techniques up to now, mainly passive devices have been attempted such as low cost RFID transponders, various types of sensors, memories, photo-voltaic cells, displays or batteries while the development of active components as diodes and transistors has been demonstrated, though only in low UHF (RF) bands [8,9,10]. Trends are moving to higher speeds, resolution, and frequencies without compromises in flexibility, environmental friendliness, and low cost. In order to overcome these challenges, novel approaches to manufacture electronics and RFID systems are needed in terms both of alternative materials, processes and characteristics.

III. INKJET-PRINTED TAG

As mentioned in the previous section, inkjet printing is one of the potential and very promising solutions for the future of "green" electronics fabrication. Modern inkjet printers operate by propelling tiny droplets of liquid down to 1 pico liters (pl) which results in the accuracy that conventional methods of fabrication yield such as several microns. Not to mention that inkjet printing utilizes a method of fabrication that uses material to be printed such as conductive paste, which rapidly fabricates prototype circuits without iterations in photolithographic mask design or traditional etching techniques that have been widely used in industry. Printing is also completely controlled from the designer's computer and utilizes artwork files such as the ones used to create masks and reads them directly, transferring them into a pattern on a substrate; hence, it does not require a clean room environment [11] and may be done in a laboratory environment. The print-head,which attaches to the materials cartridge, consists of a piezo-driven jetting device with integrated reservoir and heater [12] and is responsible for the dimensions and accuracy of the printed structures.

The savings in fabrication/prototyping time that inkjet printing brings to RF/wireless circuits is very critical to the ever changing electronics market of today, verifying its feasibility as an excellent prototyping and mass-production technology for next generation electronics, especially in RFID, wireless sensors, handheld wireless devices (e.g. 4G/4.5G cell phones), flex circuits, and even in thin-film batteries [13].

Printed electronics such as: passive circuitry (transmission lines, antennas, pads for wiring), logic, display, and power supply will have the desired characteristics of: low cost, disposability, and the potential of the familiar roll-to-roll processing currently used in printing industry.

On the other hand, several organic and low cost substrates have been identified to complement inkjet-printing technology, such as paper and liquid crystal polymer [14, 15]. [14] talks about the benefits of using paper as a substrate for high-frequency applications, reporting its very good electrical/dielectric performance up to at least 1 GHz. [15] briefly discusses the use of LCP as a flexible organic substrate that has excellent performance up to 110 GHz. For instance [14] talks about the potential of using ink-jet printing on paper substrate for the application of passive RFID, while [16] describes how inkjet printing of an antenna along with its with pads may be utilized for the mounting of discrete devices such as sensor, micro-processor, capacitors, and battery for the interconnections of a complete wireless sensor device. A photo taken under a fiducial camera of conductive ink on paper substrate is shown in the Fig. 1 below.

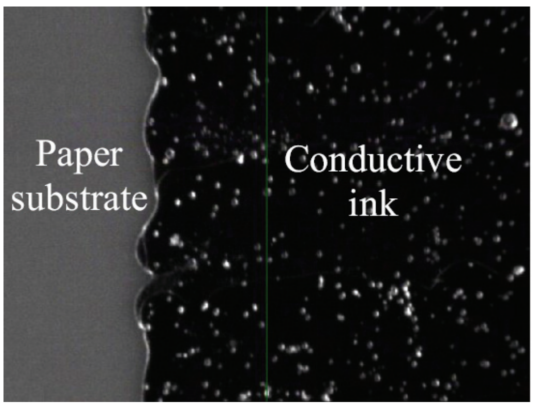


Fig. 1. Photograph of conductive ink on paper under a fiducial camera.

After introducing the paper-based substrate into the low-cost RFID tag design methodology, conductive ink has become the major cost factor of an RFID tag. Further reduction of the cost requires the optimization work on the ink's side. Minimizing the amount of ink used per antenna will save thousands of dollars in the mass production. The investigation of minimizing the ink usage by reducing solid printed surfaces with alternative design, while maintaining the tag antenna performance is achieved in this section.

Figure 2 shows the step by step process performed to gradually reduce the amount of conductive ink utilized, starting with the first version of the "solid" dipole antenna as shown in Fig. 2a. One can clearly observe from the current distribution simulation in the figure that the highest concentration mainly occurs closest to the center of the radiating body. Based on this phenomenon, the next designs were realized. Fig. 2b shows an alternative design with thin wire grid of width 0.3 mm and resulting in a quite similar performance as depicted in Table 1. Likewise, Fig. 2c and Fig. 2d show the next steps in the antenna

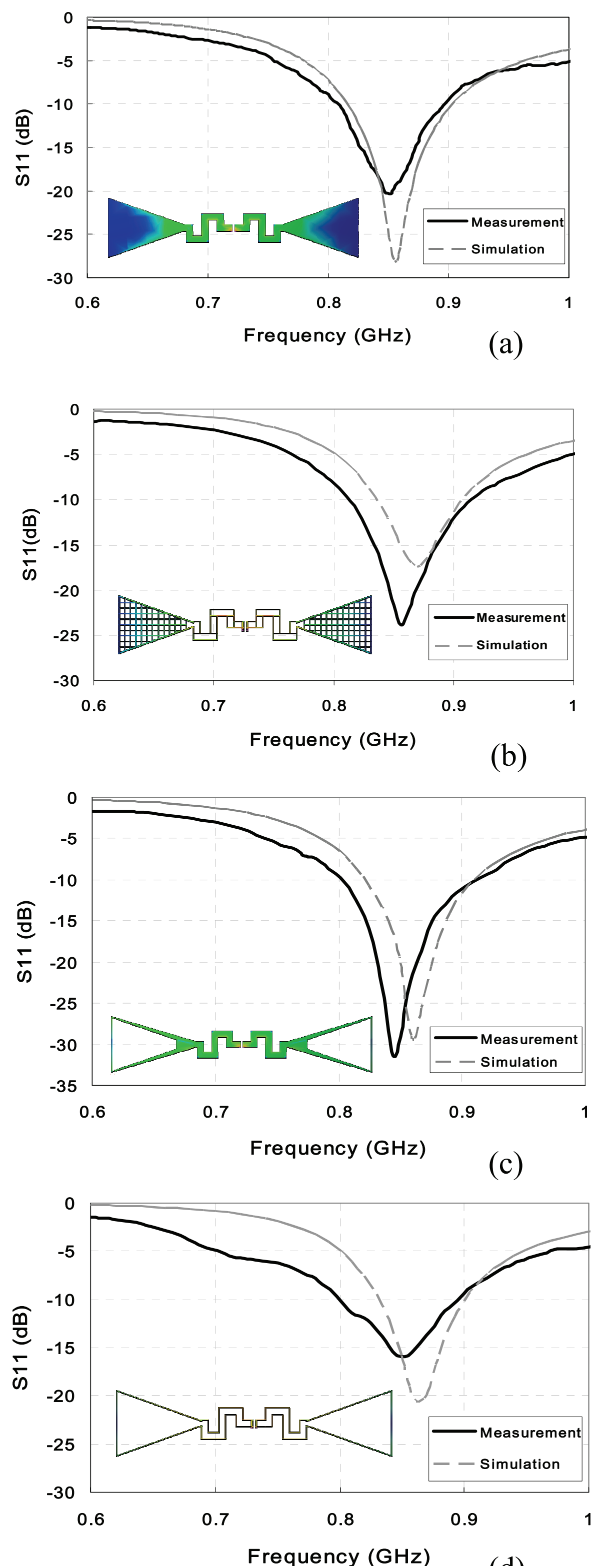


Fig. 2. Topology and return loss comparison of four inkjet-printed antenna designs at European RFID band.

Table 1: Performances comparison for the antennas shown in Fig. 2.

	BW (%)	*EFF. (%)*	*GAIN (dBi)*
(a)	10.1	99	1.94
(b)	8.66	91	1.61
(c)	10.3	99	2.03
(d)	7.9	89	1.66

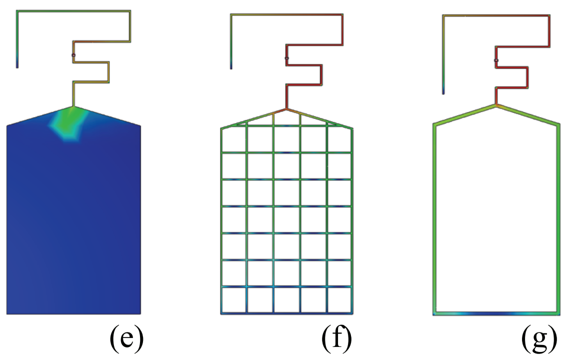


Fig. 3. Topology of inkjet-printed antenna designs of a commercial tag at US RFID band.

Table 2: Performances comparison of the antennas shown in Fig. 3.

	BW (%)	*EFF .(%)*	*GAIN (dBi)*
(e)	5.4	90.6	1.48
(f)	5.4	90.7	1.48
(g)	5.2	90.4	1.49

design while aiming towards optimizing and minimizing the amount of ink used as mentioned previously. It is to be noted that in all the plots (Fig. 2a through Fig. 2d), one can argue that the measurement results yield good comparison with the theoretical data. Furthermore, the performance of the final design shown in Fig. 2d features a bandwidth of 7.9% covering the European UHF RFID band.

The difference between the first and the last case, in terms of ink saved, is about 96%. As a trade off, the radiation efficiency decreases slightly from 99% to 89% while the antenna gain from 1.94 dBi to 1.66 dBi.

The same design topology can be used to lower the cost of existing commercial RFID tags. Fig. 3 illustrates the design of a commercial RFID tag which has been widely used on toll road collection applications. The monopole ground costs a large area for the conductive ink. The gradual reduction of ink for the alternative designs can be noticed in Fig. 3. The antenna performance is listed in Table 2. The ink saved for the antenna shown in Fig. 3g is about 94% compared with the one in Fig. 3e.

IV. FREQUENCY DOUBLING RFID TAG FOR HARMONIC RADAR

This section will be devoted to address another major challenge in the RFID world, the integration of nonlinear devices in a cost and power-effective way that could be applicable in the very stringent space requirements of RFID's (potentially in the additional space created by designs similar to the one presented in the previous section). Without loss of generality, and for simplicity reasons, this section will focus on the discussion of a frequency doubling tag based on a crossed-dipole structure and UHF diodes. Such a tag is useful for harmonic radar application and seems to be a good candidate for implementation exploiting fully green processes.

One-bit RFID systems are commonly used to check and monitor the possible presence of a transponder in the interrogation zone of a reader by means of simple physical effects [17]. Among various operating principles, the generation of harmonics is reliably adopted in the microwave frequency range, leading to the harmonic radar concept [18, 19]. Such a concept has recently been exploited in avalanche rescue systems to precisely localize victims buried under the snow [20]. The harmonic radar works as follows. A tag with aerial antenna and diode bounces back to the searchers a directional radar signal. Because of the diode nonlinearity the reflected frequency is doubled with respect to that used to illuminate the tag itself. Such a signal can easily be detected by means of a microwave receiver.

In order to make this kind of rescue systems really effective, mountain walkers or climbers and skiers should be equipped with one of these frequency-doubling tags. A method could be that of embedding the tags directly into the sky-pass cards. To this purpose both paper-based antennas [5] and organic diodes [8, 9] can be used to provide a completely green solution at very low production costs.

A structure that is particularly suited to the implementation of frequency doubling tag has already been proposed in [21]. Such a structure exploits two dipoles in a crossed configuration and four diodes and has the advantage to separate fundamental and second harmonic antennas.

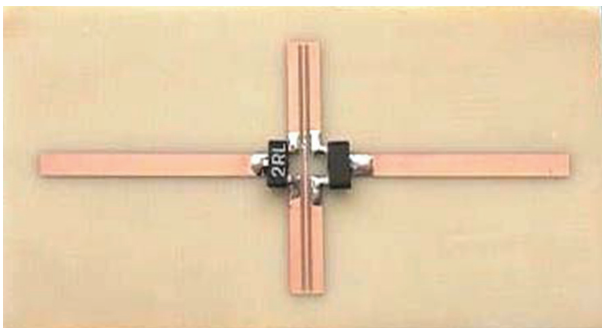
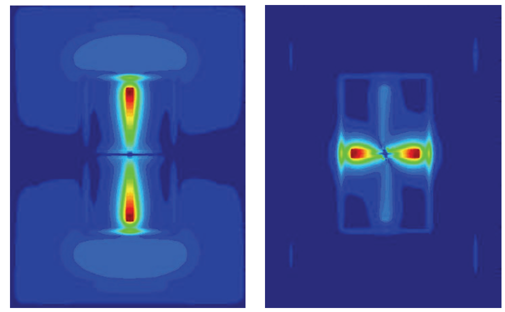


Fig. 4. Photograph of the proposed frequency doubling tag. The length of the longest l_0 dipole, corresponding to the double of the shortest one l_1, is $l_0 = 2l_1 = 32$mm. The substrate thickness is h = 0.8mm while its dielectric constant is $\varepsilon_r = 3.38$.

As shown in Fig. 4, a prototype of this frequency doubling tag has been realized on plastic substrate and consists of two crossed $\lambda/2$ dipoles. The longest dipole receives the incoming power at the fundamental frequency $f_0 = 3.5$GHz, whereas the shortest dipole transmits the generated power at the doubled frequency $2f_0$ in an orthogonally polarized orientation. The multiplication is achieved by four diodes in a bridge configuration, thus forming a fully balanced multiplier bridge. Although the diodes are operating self-biased and no external DC-supply is necessary, a return for the generated DC-component must be provided for proper operation of the multiplier itself. This is done with a thin metal strip which is embedded in the short dipole connecting its outer ends. Thus a sufficient amount of inductance is provided to avoid a major disturbance of RF performances. The proposed tag was realized on a plastic substrate with $\varepsilon_r = 3.38$, a value very close to that of paper ($\varepsilon_r = 3.2$~3.8). Moreover the layout of the crossed dipole antennas does not present critical dimension and is completely uniplanar (no bias needed). Therefore it is suitable for paper-based implementation. The FDTD simulation of E-field patterns is shown in Fig. 5.



(a) (b)

Fig. 5. FDTD simulation of E-field patterns: (a) the longest dipole is excited by a plane wave at f_0 having the E-field parallel to the dipole itself; (b) the diode quad generates a $2f_0$ frequency component which is emitted by the shortest dipole.

V. CONCLUSION

This paper introduces various new, environmentally-friendly developments in the area of UHF RFIDs. The introduction of optimal-metallization printed antennas and the effective integration of diodes could potentially lead to the first truly “green” low-cost generation of RFID-enabled devices.

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Since 2003 he has been in the steering committee of CEM. In that same year he was a member of the spin off committee of the University of Perugia, in

2005 he founded a second spin off company: DiES (Digital Electronic Solutions) Srl. In 2007 he was the chairman of the VII Computational Electromagnetic in Time Domain workshop; in 2008 he was a member of the Steering Committee of the International Microwave Symposium (IMS) held in Atlanta; he was the guest editor of the special issue of the International Journal of Numerical Modelling on the VII CEM-TD; he was appointed as chairman of Sub Committee in the TPC of IMS Symposium. In the same year he was nominated as representative for Italy in the Management Committee of COST Action IC0803, RF/Microwave Communication Subsystems for Emerging Wireless Technologies (RFCSET) where he is currently operating as Work Group leader and as the responsible for Short Term Scientific Mission (STSM) selection. Again in 2008 he was the Co-PI (Principal Investigator) of the Project ADAHELI (project founded by the Italian Space Agency –ASI for the solar observation from the satellite and he has been nominated Director of the Scientific end Technology Committee of the Risearch center “Il Pischiello”. In 2009 he was nominated vice-chairman of the new MTT Technical Committee TC-24 “RFID-Technologies”

His research interests mainly focus on the design of high frequency electronic circuits and systems, including the development of numerical methods for electronic circuit analysis.

In these fields he has published more than 160 contributions to International reviews and peer reviewed conferences, the interest in which is testified by an ISI-HF index of 12.