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Published in IET Microwaves, Antennas & Propagation
Received on 28th July 2010
Revised on 4th February 2011
doi: 10.1049/iet-map.2010.0344

Special Issue on RF/Microwave Communication Subsystems for Emerging Wireless Technologies

ISSN 1751-8725

Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology

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Abstract: This work deals with the design and fabrication of antennas for radio frequency identification (RFID) tag devices operating in the low microwave frequency range. Paper substrate material and inkjet printing process have been used to guarantee mechanical flexibility and ultra-low production costs of the antenna. A new antenna design methodology has been developed with the purpose to minimise the amount of both substrate material and conductive ink. The first goal is achieved by reducing, for a given frequency, the antenna size. The second goal, instead, is pursued by studying the surface current density distribution along the antenna and removing the metal material where such a current density is negligible. The above methodology has been applied to several antennas designs ranging from a windshield sticker tag to an RFID-SAW antenna. Moreover a 3.5 GHz crossed-dipole tag, based on the frequency-doubling mechanism, is reported along with a possible modification to enable wireless sensing. The experimental characterisation of these prototypes validates the proposed design methodology opening, in the mean time, the possibility for ultra-low cost mass production of RFID tag devices based on paper materials.

1 Introduction

Flexible electronics, a technology that has witnessed significant attention and investment in diverse engineering research and development fields, is increasingly important in today's growing market for devices demanding shape adaptability, light weight and space savings. Flexible electronics also allow the screen printing and more recently the inkjet printing on substrates such as paper and liquid crystal polymer (LCP). These are especially important in communication and identification systems, where stringent specifications have to be met often along with conformal electronics. In a similar way, the substrate material and the related integration techniques are becoming more than a simple research topic, this because of the ever growing demand for low-cost and power-efficient broadband wireless electronics almost in a ubiquitous fashion.

Several aspects make the paper material an outstanding candidate as a low-cost substrate for radio frequency identification (RFID) and other RF applications. Paper, an organic-based substrate, is universally available: the high demand and the mass production of paper has made it one of the cheapest material. In addition, from a manufacturing point of view, paper is well suited for reel-to-reel processing, thus mass fabricating RFID inlays on paper becomes more feasible once determined an inkjet printing process for RFID antennas followed by assembly of ICs and/or other microelectronic devices on board. Furthermore, there are other characteristics of paper that contribute to its selection. That is its low surface profile which, with the appropriate plastic coating that makes it similar to photographic or inkjet paper, becomes suitable for fast printing processes such as direct write methodologies or inkjet printing of electronics instead of the traditional metal etching techniques. A fast process, like inkjet printing, can be used efficiently in conjunction with appropriate interconnecting methods to produce multilayer electronics on/in paper [1]. This also enables components such as: antennas, ICs, memories, batteries and/or sensors to be embedded on/in paper modules.

The inkjet printing technology is generally faster and lower cost than other additive manufacturing technologies, not to mention it is easier. Printing polymers (conductive polymers) and functional materials on cellulose-based substrates (CBS) has also been achieved. Organic materials can be printed and patterned using various techniques (like flexo, gravure, offset, screen, inject etc.) [2–4] 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, although only in low UHF (RF) bands [5–7].

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 of alternative materials, processes and characteristics. Moreover while the consumer market in the last few years focused on the improvement of some particular characteristics in RFID applications such as the need for light weight, space saving as well as economical and environmental friendly electronics, another major challenge is represented by the integration of sensor nodes and passive RFID tags.

Antennas are key components of RFID tags both from cost and functional point of views. First of all, antennas have rather large mechanical dimensions and, therefore they require a significant amount of substrate material to be manufactured. Second, if a printing process is adopted for the fabrication of the metal structures, the quantity of conductive ink is proportional to the metalised area of the antenna. From these two observations emerges that the cost reduction of a tag device can be mainly achieved by optimising the antenna design. Reduction of the antenna size for a certain fixed frequency (and thus reduction of the needed substrate material) and of the conductive ink amount are the two main strategies that can be adopted.

With respect to the functional point of view, antennas determine, together with the chip power consumption, the reading range of passive tags. Moreover, in chip-less tags, the antenna electrical properties (resonance frequency, polarisation, radar cross-section etc.) are used to encode the information.

In this paper the above points will be developed through several design examples. Techniques for size reduction and conductive ink optimisation will be reviewed. Chip-less frequency-doubling tag and tag sensors are also described. The material is organised as follows. Section 2 summarises the state-of-the-art of the inkjet printing technology applied to the fabrication of paper-based antennas. In particular, the problem of conductive ink reduction is treated with a systematic approach. Section 3 is then devoted to the development of several antenna designs ranging from a windshield sticker tag to an RFID-SAW antenna design. Moreover, a 3.5 GHz chip-less tag based on the frequency-doubling mechanism is reported along with a possible modification to enable wireless sensing. General considerations on the paper-based antennas and tag design will be finally drawn in Section 4.

2 Inkjet-printed antennas on paper substrate

In this section inkjet-printed RFID tags on paper substrate are examined as a solution for a 'environmentally friendly', fast and ultra-low-cost mass production. Inkjet printing is a new technology, the development of which is supported by strong need in industry for rapid prototyping and 'just-in-time methods'. The need is mainly due to the desire of fast fabrication of circuits without iterations in photolithographic mask design. Inkjet printing is a direct-write technology by which is possible to transfer the designed pattern directly into the substrate. Besides, unlike etching, that is based on removing unwanted metal from the substrate, with inkjet printing there is no waste of ink since the single ink drop is jet into the desired position. In the continuous mode inkjet printing system, the drop breaks off from the jet when an electrostatic field is applied, referred to the charging field, and thus acquires an electrostatic charge. Another electrostatic field deflects the charged drops so that they are directed to the desired position. The drops are continuously produced and their trajectories are varied by the amount of charge applied. In the 'drop-on demand' mode, the voltage is applied only when the drop is desired.

Demand-mode inkjet system has no fluid recirculation requirement and this makes their use as a general fluid micro dispensing technology more straightforward than the use of continuous mode technology. In addition, piezoelectric demand mode inkjet printing does not create thermal stress on the fluid [8]. In the latter research, demand mode inkjet printing system is applied. In Table 1, the motivations of using inkjet printing technology on paper substrate with silver nanoparticles as ink are summarised.

Prototyping using inkjet printing technology becomes a powerful and time efficient method for RF/wireless circuits. In addition, inkjet printing will also cut down the cost of manufacturing by replacing existing manufacturing techniques in wireless sensors and RF handheld devices. To cite an example consider the ability in printing different materials such as thin-film batteries [9].

Several organic and low-cost substrates have been identified to complement inkjet printing technology, such as paper and liquid crystal polymer. The benefits of paper as a substrate for high-frequency applications are discussed in [10] where the electrical/dielectric performance up to 1 GHz are reported. In [11] the use of LCP as a flexible organic

Table 1 Inkjet printing on paper substrate with silver nanoparticles ink: motivations

	Motivations
PAPER as substrate	environmentally friendly and low cost
	large reel to reel processing
	low surface profile with appropriate coating
	compatible for printing circuitry by direct write methodologies
	host nano-scale additives (e.g. fire retardant textiles) can be made hydrophobic
	dielectric constant ε_r (~3) close to air's, allowing EM waves to penetrate substrate easily with minimum (5–6%) power reflection
	via holes with typical diameter of 200 μm have been fabricated
inkjet printing with silver ink as deposition technique	1 and 10 pl cartdridges: 10 pl drops give ~21 μm diameter
	10–12 cP (centiPoise); can be heated to 70°C to decrease it; up to 30 cP has been jetted
	drop placement accuracy ± 10 μm gives a resolution of 5080 dpi
	drop repeatability about 0.5%
	silver nanoparticles ink conductivity varies from 0.4 to 2.5 $\times$ 10 S/m, depending on the curing temperature

doi: 10.1049/iet-map.2010.0344

Current distribution	*BW (%)*	*GAIN (dBi)*
case (a) 	10.1	1.94
case (b) 	8.66	1.61
case (c) 	10.3	2.03
case (d) 	7.9	1.66

Fig. 1 *Topology and performance comparison of four inkjet-printed antenna designs at European RFID band (868 MHz)*

substrate is shown with excellent performance up to 110 GHz. In [12] the inkjet printing of an antenna along with its pads is experimented. This antenna may be utilised for the mounting of discrete devices (sensors, micro- processors, capacitors, batteries) and for the interconnections of a complete wireless sensor device.

2.1 Silver ink optimisation

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 instead. The investigation of minimising the ink usage by reducing solid printed surfaces with alternative design, while keeping the tag antenna performance is achieved in this section. The step-by-step process performed to piecemeal reducing the amount of conductive ink utilised is reported in previous work [13] and in Fig. 1, starting with the first version of the 'solid' dipole antenna as shown in case (a).

It can be observed from the surface current density distribution in Fig. 1 (simulated data) that the highest concentration is mainly occurring close to the edges of the radiating body. Based on this phenomenon, the next designs were realised. Case (b) shows an alternative solution with thin wire grid of width 0.3 mm and resulting in a quite similar performance as depicted in Fig. 1. Likewise, cases (c) and (d) show the next steps in the antenna design while aiming towards optimising and minimising the amount of ink used as mentioned previously. It has to be observed that the performance of the final design shown in Fig. 1 features a bandwidth of 7.9% covering the European UHF RFID band as shown in Fig. 2. From the first to the last case the ink saved is about 96%. As a trade off the antenna gain decreases from 1.94 to 1.66 dBi. It is worth noticing that the optimised designs resemble wire implementations of bow-tie antennas typically seen in the HF–VHF range.

3 Inkjet printed tags

In this section four examples of RFID tag both inkjet printed on paper substrate are reported: the first one is a commercial windshield sticker tag designed and fabricated following the ink optimisation method; the second is an RFID-SAW antenna tag; the third is a frequency-doubling tag based on a crossed-dipole structure and Schottky diodes; the fourth and last is an extension of the crossed-dipole structure incorporating a resistive sensing element.

3.1 Windshield sticker tag

To compare the performances and verify the effectiveness of using current distribution plot as a guide to reduce the ink usage, an RFID device based on an Intermec Windshield Sticker tag is considered as the first case of study.

This commercial tag has been widely used on toll road collection applications. However, the monopole ground costs a large amount of conductive ink. The current distribution and the modified schematic layout are depicted in Fig. 3, showing that only the edge of the monopole ground is remained in the modified design. The meander line dimensions of the monopole arm were also modified to ensure a good matching to the IC chip impedance while reducing its size. The paper substrate used to provide a mechanical support has an impact on the antenna input impedance. The amount of the conductive ink used is around 12% of the original design. Fig. 3 shows the comparison between original and ink-optimised tags with respect to antenna gain and bandwidth.

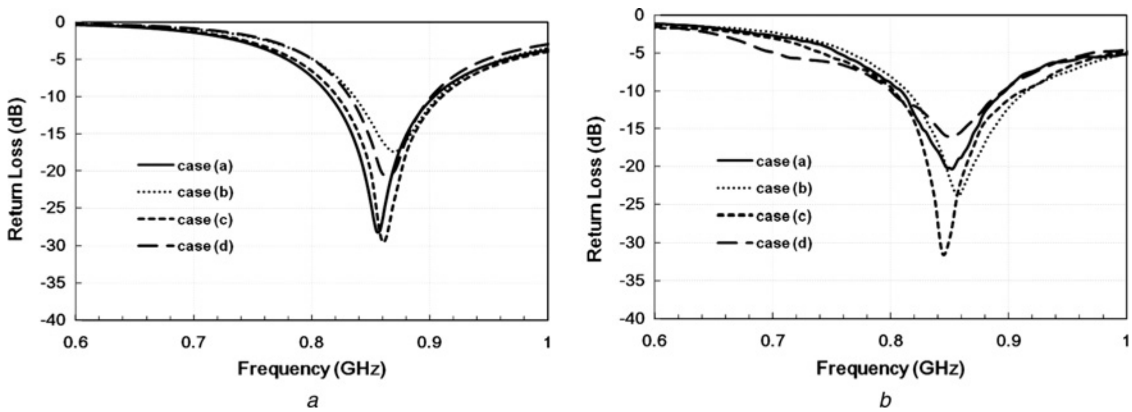


Fig. 2 *Return loss comparison of the four inkjet-printed antenna designs at European RFID band*

a Simulated
b Measured

doi: 10.1049/iet-map.2010.0344

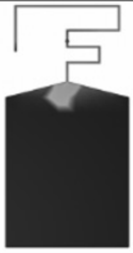
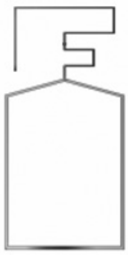
Current distribution	*BW (%)*	*GAIN (dBi)*
	5.4	1.48
	5.2	1.49

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

Comparison in terms of relative bandwidth and antenna gain as a function of the ink-optimisation

Fig. 4 shows a photograph of the fabricated prototype whereas Table 2 reports the main tag parameters. In this table the equivalent isotropic radiated power is denoted as EIRP, τ is the power transmission coefficient between the tag antenna and the RFID IC chip, and Pth is the threshold power needed to activate the RFID IC chip.

It is important to recall that $\tau = 0.96$ (96% power transfer) is obtained as a result of the good conjugate matching between antenna and chip impedance.

To measure the maximum reading range the tag was attached on a glass surface with a spacer whose thickness was 0.5 mm. With a circularly polarised reader the reading range was measured to be 4.0 m. As Table 3 depicts, the comparison of the measured reading range reveals a higher

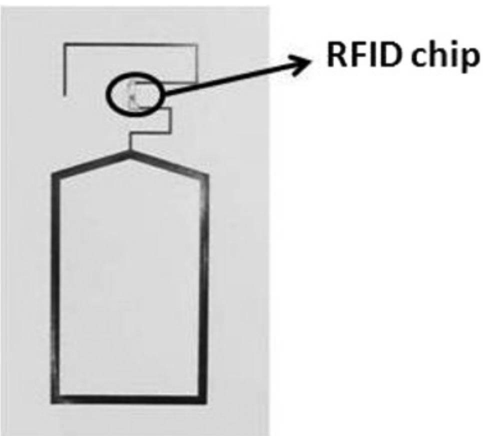


Fig. 4 *Photograph of the proposed inkjet-printed RFID tag on paper-based substrate with ink-usage after the ink optimisation*

Table 2 Windshield Sticker tag: main system parameters achieved with the ink-optimised monopole

EIRP	Gain (G)	Antenna (Zant)	Chip (ZIC)	τ	Pth
4 W	1.49 dBi	43.7 + j123 Ω	33 − j112 Ω	0.96	−9 dBm

range for the modified tag; this can be explained by a better impedance matching achieved during the design of the monopole arm. Overall, 88% of the conductive ink was saved while a competing performance was achieved.

3.2 RFID-saw antenna tag

In this paragraph an example of RFID-SAW antenna tag design is presented. SAW-based RFID is an approach that solves regulatory issues on a worldwide scale because it uses low-power reader signals and operates in 2.45 GHz.

A Dimatix DMP-2800 inkjet printer was used to carry out the inkjet printing on paper substrate. A conductive silver nano-particles ink is adopted. In Fig. 5*a* a photograph of the printed antenna together with the relevant tag circuitry is shown. The RF SAW chip was attached to the antenna using a conductive silver epoxy compound as illustrated in Fig. 5*b*.

The antenna design focused on the reduction of the silver ink utilised, following the step-by-step procedure already explained in Section 2. The very common bowtie antenna shape previously discussed (see Fig. 1) was modified to match the impedance of the SAW-RFID chip at 2.45 GHz. Compare to the free-space wavelength ($\lambda_0 \sim 122.5$ mm) the overall antenna size is about $0.34\lambda_0$, thus considerably shorter than $\lambda_0/2$. To obtain a good antenna efficiency at the operating frequency, the entire circuit was printed with several layers of silver ink thus resulting in an optimum conductor thickness. The dimensions of the central part of the antenna were reduced while a meanderline shape was almost maintained. The external part of the two arms was changed with respect to Fig. 1. In particular a 'W-shape' is adopted, with the purpose of further reducing the dimensions of the overall structure while following the ink optimisation technique already developed. In Fig. 6 the comparison between electromagnetic simulations and measurements of the return loss of the SAW-based RFID tag is shown. In Fig. 7 the current distribution and the radiation pattern are reported. The gain of the realised antenna is about 1.9 dBi.

3.3 Crossed dipole frequency-doubling RFID tag on paper

The integration of non-linear devices in a cost-effective way will be the focal point of the third example.

In particular the section will be devoted, without loss of generality and for simplicity reasons, to the discussion of a frequency-doubling tag based on a crossed-dipole structure and Schottky diodes. Such a structure can be realised on

Table 3 Comparison of the read range of the windshield tag

	Ink-optimised monopole	Original design
ink-usage, %	12	100
read distance, m	4.0	3.9

doi: 10.1049/iet-map.2010.0344

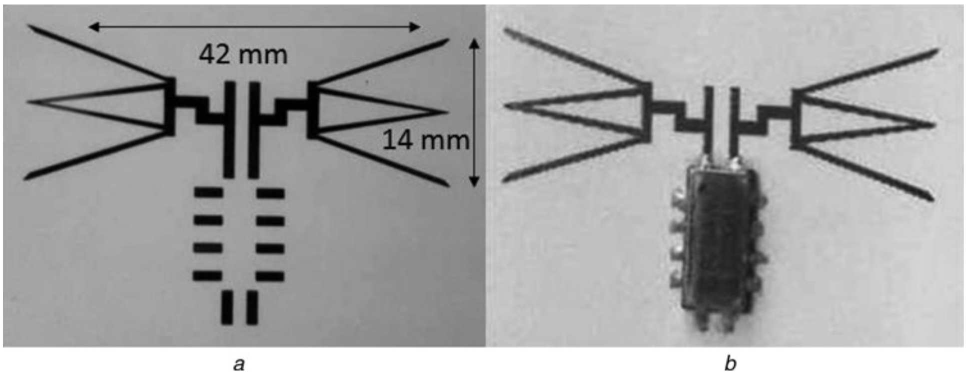


Fig. 5 *Photograph of the inkjet printed antenna and circuit and photograph of the same printed sample with the mounted SAW based RFID*
a Antenna
b Antenna with SAW tag

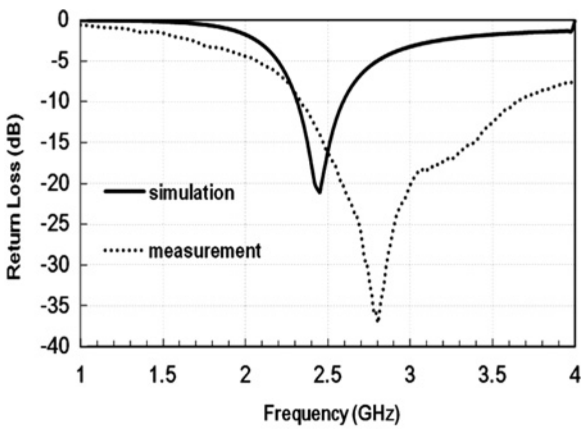


Fig. 6 *Return loss of the SAW-based RFID tag*
Comparison between electromagnetic simulations and measurements

flexible substrate like plastic, PCB and paper. Thus a tag is useful for harmonic radar application and seems to be a good candidate for implementation based on 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 [14]. Among various operating principles, the generation of harmonics is reliably adopted in the microwave frequency range, leading to the harmonic radar concept [15, 16] that has also recently been exploited in avalanche rescue systems to precisely localise victims buried under the snow [17]. In the tag with aerial antenna and diode a directional radar signal bounces back to the searchers. The diode non-linearity can be exploited so that the reflected frequency will be doubled with respect to that used to illuminate the tag itself. Such a signal can easily be detected by means of a microwave receiver without being masked by reflections from the surrounding scenario even if any modulation is applied to the carrier.

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 [2] and organic diodes [5, 6] can be used to provide a completely green solution at very low production costs.

The structure proposed in [18] is particularly suited for the implementation of frequency-doubling tag. 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. 8 shows the layout of the frequency-doubling tag. 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 polarised orientation. The multiplication is achieved by four diodes in a bridge configuration, thus forming a fully balanced multiplier bridge. Being the diodes self-biased without external DC-supply, a return for the

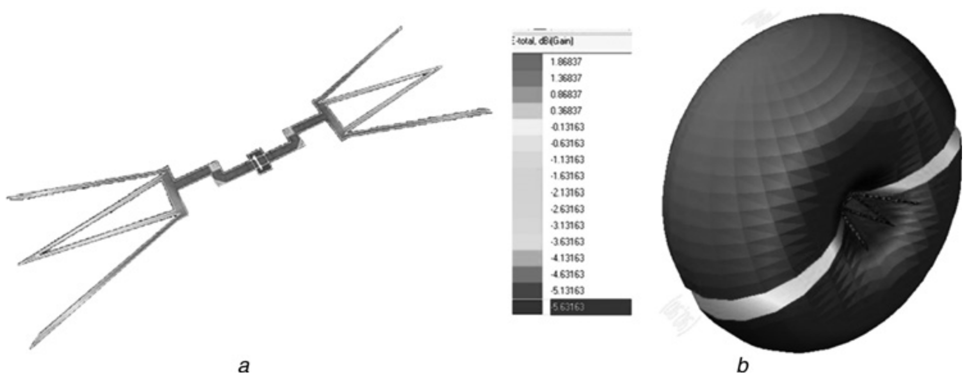


Fig. 7 *SAW-based RFID tag*
a Current density
b 3D radiation pattern

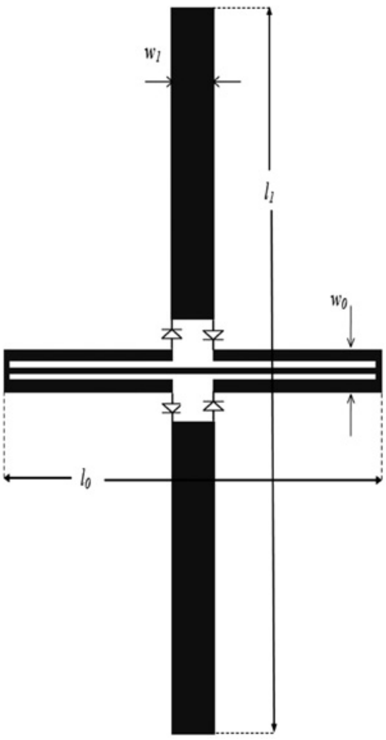


Fig. 8 *Layout of the crossed-dipole frequency-doubling tag operating between $f_0 = 3.5$ GHz (interrogating frequency) and $2f_0 = 7$ GHz (tag response)*

self-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 together with DC path to avoid a major disturbance of RF performances. The proposed tag was first realised on a plastic PCB substrate with $\varepsilon_r = 3.38$, a value very close to that of paper ($\varepsilon_r = 3.2 - 3.8$) [18].

Since the layout of the crossed dipole antennas does not present critical dimensions and is completely uniplanar (no

Fig. 9 *Photograph of the crossed-dipole frequency-doubling tag based on paper substrate*

Schottky diode bridge is mounted exploiting conductive epoxy

vias needed), it has been suitable for paper-based implementation. Fig. 9 shows the crossed-dipole printed on paper substrate. Silver conductive epoxy has been applied to glue the diodes on the substrate. The epoxy had to be cured to improve its conductivity (2 h in a controlled oven at 120°C temperature). Fig. 10 shows the test bench that has been set up for measurement purpose [19]. A frequency source generates the 3.5 GHz input frequency while a 20 dBm power signal is sent to the transmitting antenna. A helix antenna receives the doubled frequency (7 GHz) while the received power is measured by a spectrum analyser.

Fig. 11 reports an experimental comparison between the plastic PCB and paper tag in terms of received power at the distance of 10 cm. Fig. 12 confirms that the paper tag has a lower conversion loss by showing the received power level versus the distance between the tag and the receiving antenna. The lower conversion loss of the paper tag can be attributed to the non-negligible resistance of the conductive ink path. From DC measurements we noticed that the series resistance of the longest dipole is 2.5 Ω per arm. Similarly the shortest dipole shows 5.5 Ω per arm and the thin metal strip inside the shortest dipole feature about 9.3 Ω. Moreover, the diodes in the plastic PCB prototype have a threshold voltage of 0.28 V, whereas diodes with a threshold voltage of 0.38 V were used for the paper tag (this difference depends on different lots of the same HSMS 8202 devise).

Another experiment has been carried out with the purpose of properly investiging the reasons behind the losses. The paper tag has been placed at a fixed distance of 10 cm from the helix antenna reader. The transmitting antenna illuminates the tag with a power of 20 dBm. The interrogation frequency instead has been varied between 3 and 5 GHz (the doubled frequency is changed accordingly). From the measurement results depicted in Fig. 13, it can be observed that the crossed dipole seems to be shifted in frequency, showing a better performance at 9 GHz (4.5 GHZ of interrogation frequency). The frequency shift can be attributed to the uncertainty in both the intrinsic diodes capacitances and paper substrate dielectric constant. Although a further optimisation is needed, these results show that paper substrates and inkjet technology are suitable for RFID applications. Some further efforts should also be devoted to improve the technological aspects such as passivation and components assembly.

3.4 RFID enabled gas sensor

According to recent studies there has been a growing interest in RFID enabled sensor nodes realised with inkjet printable materials like silver nanoparticles and single-wallet carbon nanotube (SWCNT) ink. In this section we prove the feasibility of a sensor node integrated in the crossed dipole frequency-doubling RFID tag.

The frequency-doubling tag structure has been modified as in Fig. 14 by replacing the high impedance metal strip that connects the outer ends of the short dipole with a variable resistor and an inductor. The variable resistor models the SWCNT layer whereas the inductor accounts for possible parasitic effects. The electrical conductivity of the SWCNT film can change in presence of small quantity of gases like ammonia [20] and nitrogen oxide, so that the inkjet printed film can behave as the variable resistor required in the system.

The antenna and the variable resistor can be directly printed on paper substrate resulting in a low-cost, flexible, ‘green’ and

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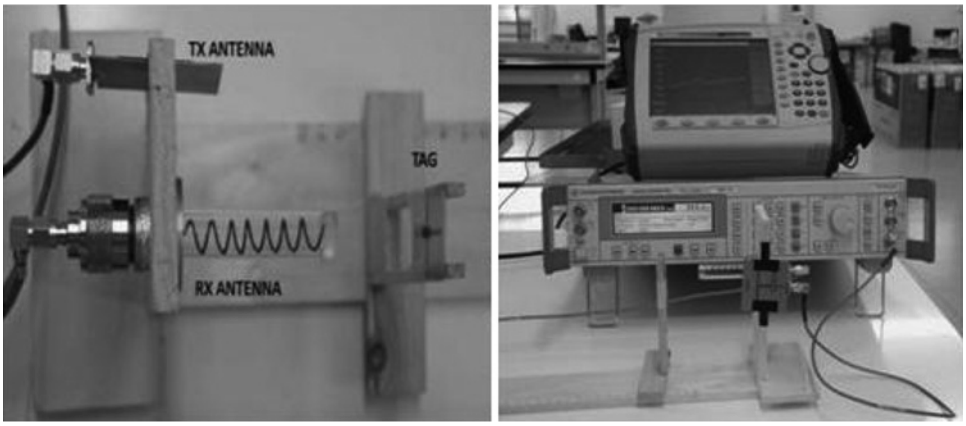

Fig. 10 *Measurement set-up for the frequency-doubling tag*

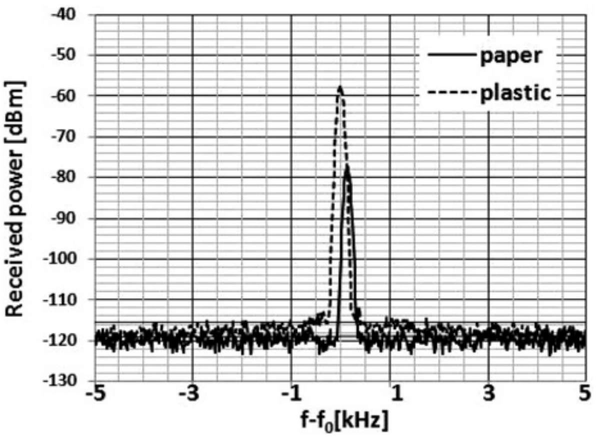

Fig. 11 *Received signal spectrum at $2f_0 = 7$ GHz: comparison between paper TAG and (prior) PCB design*

Measurements are carried-out at a 10 cm distance from the reader with a +20 dBm interrogating power

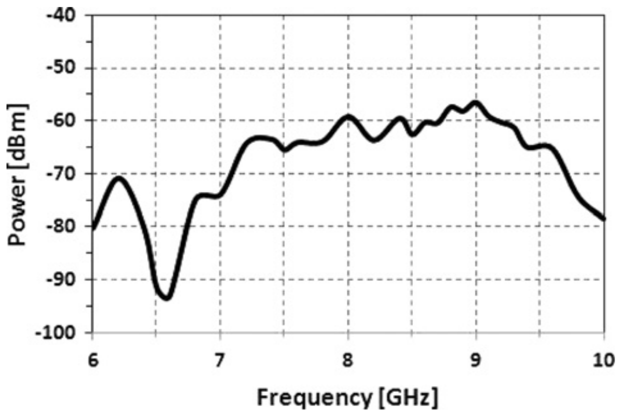

Fig. 13 *Crossed-dipole frequency-doubling tag base on paper substrate*

Received power versus frequency at a fixed 10 cm distance from the reader. The interrogating power is again +20 dBm

highly integrated RFID module. The principle of operation is the following. The resistor R_{CNT} act as a variable load connected in parallel to the shortest dipole and thus at the frequency-doubler output. By varying R_{CNT} the power irradiated by the tag at $2f_0$ can be controlled. Such a control actuated by sensing the chemical substance.

To study the change in the tag behaviour, harmonic balance simulations with advances design system environment have been performed. Fig. 15 shows the conversion loss values

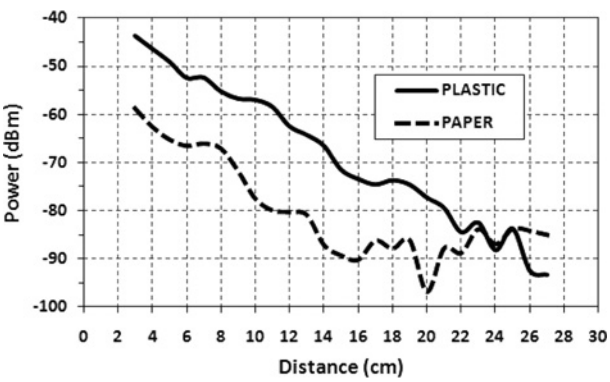

Fig. 12 *Received power against the distance for the crossed-dipole frequency-doubling tag*

Comparison between paper-based and PCB (plastic)-based prototypes. The interrogating power at $f_0 = 3$ GHz is equal to +20 dBm

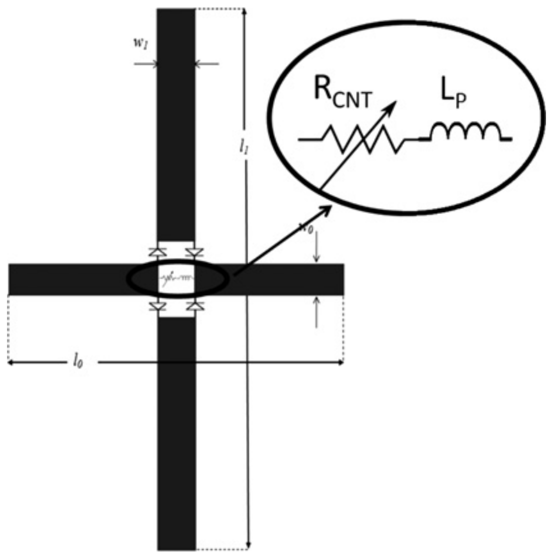

Fig. 14 *RF enabled sensor node concept*

This structure is obtain as a modification of the crossed dipole frequency-doubling tag. The resistor models a layer of Carbon Nano Tubes (CNT) whereas the inductor describe a parasitic effect. When the CNT layer senses a particular chemical substance the resistance is varied loading in a different way the shortest ($2f_0$) dipole. As a result the irradiated power depends on the sensed chemical substance

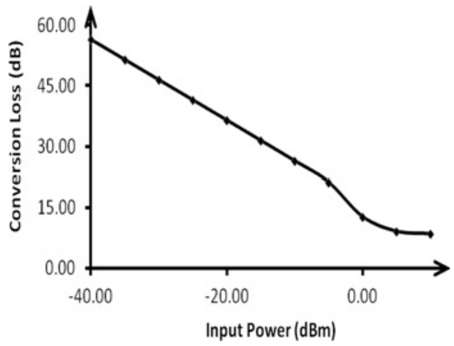

Fig. 15 *Crossed-dipole sensing tag*

Harmonic balanced simulation of the frequency-doubler conversion loss versus the received (input) power at 3.5 GHz

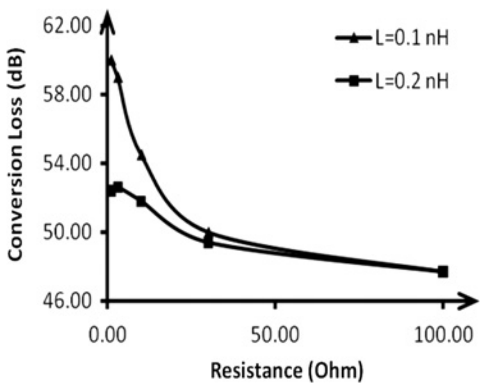

Fig. 16 *Conversion loss trend for different resistance and inductance values ($P_{in} = -30$ dBm)*

Crossed-dipole sensing tag. Harmonic balanced simulation of the frequency-doubler conversion loss for an input power (3.5 GHz) of −30 dBm. The simulations have been carried-out considering the resistance of the CNT layer as the independent variable and for two values of parasitic inductance. A conversion loss variation of more 10 dB is achieved for $L = 0.1$ nH and the resistance in the range between 5 and 70 Ω

for different input power values whereas Fig. 16 summarises the conversion loss behaviour when the resistance changes from 5 to 100 Ω. Two different values of parasitic inductance have been assumed in the simulations. The input power (Pin) is equal to −30 dBm. It can be observed that if the parasitic inductance is in the order of 0.1 nH, the conversion loss goes from 58 to 48 dB thus resulting in a remarkable (about 10 dB) control of the power irradiated at $2f_0$. Considering that some inkjet printable materials like carbon nanotubes (CNT) show sensitivity towards small quantities of gasses such as ammonia [20] and nitrogen dioxide by changing the conductivity of such materials, it is clear how the resistor shown in Fig. 14 could be replaced by some inkjet printed layers of such materials, thus resulting in an RF enabled sensor node.

4 General considerations

Some general considerations can be drawn on the basis of the research activity described in this work. First of all the adoption of paper substrate is an effective solution for the fabrication of ultra-low-cost RFID tag devices. Second, the present technology can reliably exploit inkjet printing process of both metal traces (by means of conductive ink) and sensing materials (e.g. using CNT layers). Novel RFID tags can be developed with these approaches.

In chip-based passive tags, the antenna cost can be reduced by directly applying the above results. The heterogeneous integration between chip and paper-based antenna, instead, remains an open problem. Along this direction a possible solution has been proposed in [21, 22]. In these contributions, an heterogeneous transformer is adopted. The primary winding of the transformer is realised on the paper substrate and connected to the tag antenna. The secondary winding is fabricated on the silicon chip and wired to the tag electronics (primarily to the rectifier). With this approach the internal tag circuitry is powered by magnetic coupling and no galvanic contacts are required. The antenna to chip integration can thus be reduced to a mere gluing process.

In chip-less passive tags many functions are still under development. A sensing capability can be obtained either exploiting CNT layers [20] or adopting cellulose-based microelectromechanical systems (MEMS) devices [4]. Several antenna characteristics can be used to encode information, such as the resonance frequency, the radar cross-section and the polarisation, only to name a few. A significant technological improvement is constituted by the recent development of via-hole connections [1]. With such a connection both the surfaces of a paper foil can be exploited to further miniaturise the tag circuitry.

The final goal will be, of course, that of having active electron devices (MOS transistors) directly printed on paper [23]. This futuristic view is pursued by several research groups such as illustrated in [3]. An intermediate step, however, is constituted by the development of diodes [5, 6] or, more in general, of non-linear electronic devices on paper. With these devices both frequency-doubling tags or tags based on the generation of intermodulation products [24] could be enabled.

5 Conclusions

A new design and fabrication methodology for RFID antennas inkjet printed on paper substrates has been developed. This methodology considers, as design constraints, the amount of both substrate material and conductive ink. In particular, the quantity of substrate material is minimised by reducing, for a given operating frequency, the antenna size. To this purpose meander lines are used at the feeding of both dipole and monopole antennas. The amount of conductive ink, instead, is optimised by removing the metal where the surface current density is negligible. Such a design methodology has been demonstrated by several examples and measured prototypes. It has been applied to both monopole and bow-tie dipoles with overall good electrical performances.

Another topic that has been discussed is the design of chip-less RFID tags based on paper substrates. In this kind of devices the antenna characteristics (resonance frequency, polarisation, radar cross-section etc.) are used to encode the information. In particular, it has been considered the case frequency-doubling tag exploiting a crossed-dipole geometry. The frequency multiplication is achieved by means of four Schottky diodes in bridge configuration, whereas the harmonic loading at the two frequencies is provided by the two antennas. Finally, a modification of this structure is proposed in such a way to allow for wireless sensing. To this purpose a layer of CNT can be exploited to measure the concentration of some chemical substance, such

doi: 10.1049/iet-map.2010.0344

as ammonia (NH_3). The layer is modelled as a variable resistor and placed in parallel to the shortest dipole. As a consequence the power irradiated by the tag at the doubled frequency can be controlled by the CNT layer resistance which, in turn, is a function of the chemical concentration.

6 Acknowledgments

Dr. Li Yang is acknowledge for his support. This work was partially supported by the COST Action ICO803 'RF/Microwave Communication Subsystems for Emerging Wireless Technologies (RFCSET)'.

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