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SMART PROTOTYPING TECHNIQUES FOR UHF RFID TAGS: ELECTROMAGNETIC CHARACTERIZATION AND COMPARISON WITH TRADITIONAL APPROACHES

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Abstract—Over the last few years, the active and growing interest in Radiofrequency Identification (RFID) technology has stimulated a conspicuous research activity involving design and realization of passive label-type UHF RFID tags customized for specific applications. In most of the literature, presented and discussed tags are prototyped by using either rough-and-ready procedures or photolithography techniques on rigid Printed Circuit Boards. However, for several reasons, such approaches are not the most recommended, in particular they are rather time-consuming and, moreover, they give rise to low quality devices in one case, and to cumbersome and rigid tags in the other. In this work, two alternative prototyping techniques suitable for cost-effective, time-saving and high-performance built-in-lab tags are introduced and discussed. The former is based on the joint use of flexible PCBs and solid ink printers. The latter makes use of a cutting plotter to precisely shape the tag antenna on thin copper sheets. Afterwards, a selection of tags, designed and manufactured by using both traditional and alternative techniques, is rigorously characterized from the electromagnetic point of view in terms of input impedance and whole tag sensitivity by means of appropriate measurement setups. Results are then compared, thus guiding the tag designer towards the most appropriate technique on the basis of specific needs.

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1. INTRODUCTION

Passive Radio Frequency Identification (RFID) technology is increasingly adopted in many contexts, even quite far from the canonical ones basically related to logistics. Identification of goods containing liquid or made of metal [1–6], RFID-based sensor data transmission [7–10], platform tolerant tags [11, 12], are only a few of the many possible examples where tags customized for specific applications are needed. This necessity has been acknowledged by the electromagnetic scientific community which, over the last few years, has put a great deal of effort into RFID projects. The consequent rapid proliferation of scientific works on tag design and optimization is a matter of fact [1–29]. However, such a migration of electromagnetic competences towards this emerging technology has often led to readapt laboratory facilities formerly used for other purposes. The main consequence is that, in most of the mentioned literature, designed and discussed tags are prototyped either by means of the here called PL_RPCB — photolithography on rigid Printed Circuit Boards (PCBs) — giving rise to non-flexible and cumbersome devices, or even by shaping the antennas on adhesive copper sheets through handy cutters, with obvious consequences in terms of quality, spatial resolution and repeatability. Actually, in recent years a strong effort has been dedicated to develop different prototyping techniques based on sophisticated conductive-ink printers capable to directly print the tag antenna on flexible substrates [30–34]. Moreover, special materials such as metallic nanoparticles inks [35–37] and conductive silver pastes [29] have been also adopted in this context with interesting results. Nevertheless, even if the above mentioned techniques are suitable to quickly produce precise and flexible tags having good electromagnetic performance, they are still a hot research topic and, mostly because of the cost, are not ready yet for a massive diffusion in research labs involved in RFID design. As a result, the PL_RPCB still remains, de facto, the most diffused prototyping technique also for RFID applications.

In the first part of this work, two alternative prototyping techniques suitable for built-in-lab tags are presented and discussed. The former is based on the joint use of solid ink printers and flexible PCBs (SI_FPCBs). It is worth mentioning that, despite flexible circuits are becoming a key technology in electronics [39, 40], they are rarely adopted by the electromagnetic community. Actually, their use for tag antenna prototyping, still very sporadic [41], seems to be the natural way to satisfy the requirements of flexibility, low cost and robustness of RFID tag prototypes. Finally, the combination of flexible PCBs with a solid-ink printer is the real added value. A mask of the tag antenna capable to shield the copper in case of exposure to ferric chloride, is directly obtained by adhering a wax-based ink onto the flexible PCB, thus saving much of the time and avoiding most of the steps (not completely error-free) specific of a traditional photolithographic prototyping process.

The latter alternative approach, completely new in literature, is as simple as effective. It consists of shaping the tag on flexible adhesive copper sheets by using a machine called Cutting Plotter, and of removing the extra copper manually. Indeed, despite this kind of plotter is usually thought for typographic applications, their knives are able to precisely incise even sheets of copper, thus making easy and immediate the development of tag samples. The acronym CP_FACS (Cutting Plotter on flexible adhesive copper sheet) will be used from now on to refer to such technique.

Both techniques guarantee the required flexibility of the label-type tag prototypes and promise much higher rapidity and better cost-effectiveness than traditional procedures based on rigid PCBs. Moreover, even though time-saving and flexibility are strategic, they are only two of the various characteristics that may be desired for a tag prototyping process. It is then crucial for the tag designer be provided with all the elements useful to select the most appropriate prototyping technique on the basis of specific needs. In such a context, a rigorous classification of tags realized through such techniques is mandatory.

For such a reason, in the second part of this work, three different tags (a wideband tag and two kinds of narrow-band tags) have been designed and then manufactured through both traditional and alternative prototyping approaches. Afterwards, the sets of tags have been carefully characterized in terms of antenna impedance and tag sensitivity, and results compared. Electromagnetic results are very interesting: in spite of the extreme simplicity and rapidity, the proposed methods are qualitatively comparable with those making use of rigid PCBs as substrate. In addition, differences in terms of other parameters, such as flexibility, cost and physical robustness, are extensively commented.

The paper is structured as follows: Section 2 introduces and comments on both the traditional and the alternative prototyping techniques here considered; Section 3 is dedicated to the design and realization of the tags under test, whose rigorous characterization is carried out by means of the measurement techniques briefly described in Section 4. In Section 5 results and comparisons are presented, whilst further comments and suggestions are reported in Section 6. Finally, conclusions are drawn in Section 7.

2. TRADITIONAL AND ALTERNATIVE RFID TAG PROTOTYPING TECHNIQUES

In this section, the most adopted prototyping techniques for built-in-lab tags, the PL_RPCB, is shortly recalled. Moreover, the two proposed alternative approaches, namely the SI_FPCB and the CP_FACS, are presented and discussed.

2.1. Tag Prototyping on Rigid PCBs via Photolithography: PL_RPCB

As previously stated, one of the most used and very popular prototyping technique, typically used to produce both electronic circuits and planar antennas, is the one based on photolithography processes applied to rigid PCBs, mentioned in this work as PL_RPCB. The method is very well known and, for the sake of brevity, only the list of the processes to be carried out to obtain a RFID tag prototype will be here recalled. First, a black mask of the desired tag antenna layout is printed on transparent glossy paper. Whereupon, the mask is narrowly applied on the photoresist layer of the photosensitive PCB which is then exposed for several minutes to ultraviolet (UV) light. As a result, the layout of the antenna is impressed on the PCB thus delineating a copper region shielded from the ferric chloride etching. Indeed, only the photoresist external to this region is removed when the PCB is etched with sodium hydroxide based solutions. Finally, the extra copper is removed through ferric chloride exposure. Once removed the residual photoresist and soldered the RFID chip, the rigid RFID tag is definitely completed. It is worth highlighting that both UV exposure and etching time are crucial for a successful realization of the tag antenna and that, moreover, they strictly depend on type and quality of used photoresist, acids and PCBs. Consequently, the average realization time of a single tag antenna is variable, and typically ranges from 45 to 75 minutes.

2.2. Solid Ink Based Tag Prototyping on Flexible PCBs: SI_FPCB

Different techniques for production of high frequency circuits and antennas can be based on the use of flexible instead of rigid PCBs, thus guaranteeing the precious added value of the flexibility which is usually required in RFID tags development. Several types of flexible PCBs are on the market. Among them, without loss of generality, DuPont Pyralux samples [42] have been taken into account and studied in this work. Typically, Pyralux is distributed as thin laminate sheets.

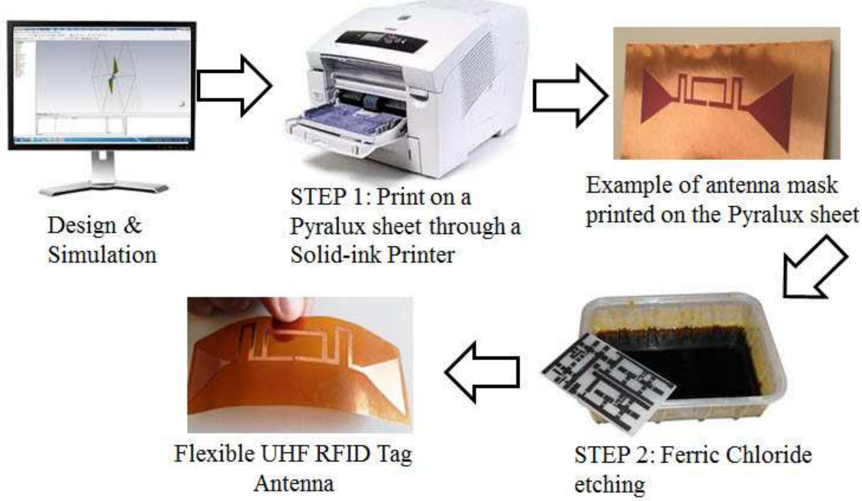


Figure 1. SI_FPCB prototyping process.

Each sheet is composed of a flexible substrate of polyamide of thickness ranging from 12 to 45 μm and a copper-clad laminate of thickness varying between 12 and 35 μm.

Based on the use of such Piralux laminates, a new very practical alternative prototyping solution, the SI_FPCB whose flow-chart is represented in Figure 1, can be introduced. As shown, only two main steps are needed. Indeed, once the antenna layout has been optimized, it is directly printed on the Piralux sheet by a so-called solid-ink printer which, differently from traditional office printers, deposit a layer of a wax-based ink which perfectly adheres on copper layers. Moreover, such solid ink at the same time shields the copper from subsequent acid etchings, which represents the second and last step of the procedure. In this way, compared with PL_RPCB, the prototyping process is greatly accelerated and simplified, as time consuming and tedious steps such as UV exposure and sodium hydroxide etching are not required anymore. Indeed, a tag is realized in less than 30 minutes, making use, de facto, only of the last step of the photolithography process. Moreover, flexibility is guaranteed and materials and costs are significantly reduced. A suitable printer costs less than 800 USD and guarantees thousands of prints with a few dollars of wax-based ink. As for the consumables, 15 USD are enough for a single A4 format pyralux sheets, whilst the ferric chloride has a negligible cost per antenna.

It is worth highlighting that the use of wax-based solid ink printers (a Xerox Phaser 8550 in the case of Figure 1) is crucial, because common ink-jet and laser printers are not appropriate at all. The former because common liquid ink does not adheres on copper, the latter because laser printers cannot print on reflecting surfaces.

As for the better resolution achievable with this technique, it strongly depends on the resolution of the printer, as happens also in PL_RPCB case. Most of solid ink printers guarantees a resolution inferior to 250 µm. Nevertheless, in the author's experience, antennas requiring resolutions better than 600 µm (very unusual in UHF RFID tag design) require a very careful realization in clean rooms and the etching time should be opportunely estimated. Vice versa, no particular precautions are needed for classical RFID antennas, where resolution higher than 1 mm are usually adopted.

2.3. Cutting Plotter Based Tag Prototyping on Flexible Adhesive Copper Sheets: CP_FACS

CP_FACS (Cutting Plotter Based Tag Prototyping on Flexible Adhesive Copper Sheets) is a novel and particularly time-saving technique useful to prototype extremely flexible and high-performing RFID tags through the use of a cutting plotter. This machine is regularly used in the graphic industry for cutting and shaping vinyl foils. Indeed, a cutting plotter is similar to a printer, but it is equipped with a precise cutting tip. In the antenna realization context, the use of cutting plotters is substantially new. The idea is to use flexible adhesive copper sheets instead of vinyl foils. In this way, in a first step the tag antenna layout can be straightforwardly shaped on the copper sheet surface. In the second and last step, the extra adhesive copper is manually removed. In Figure 2, for instance, the flow-chart of the CP_FACS procedure is reported and the two mentioned steps, the tag shaping and the extra copper removing, are highlighted.

The use of this prototyping technique promises immediate

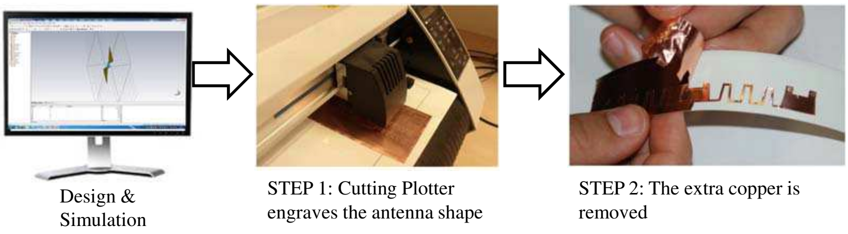
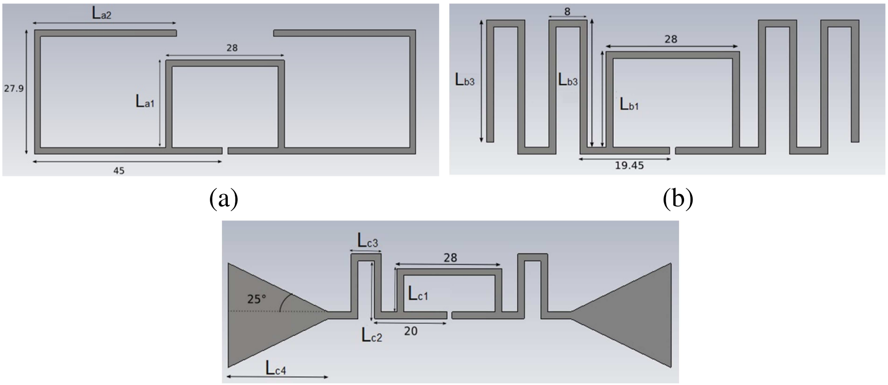


Figure 2. CP_FACS prototyping process.

advantages especially in terms of average prototyping time. Indeed, only few seconds are required to incise the tag antenna on the support and about a couple of minutes to remove the extra copper, depending on the tag complexity. Therefore, less than 5 minutes including soldering are necessary to obtain a functioning tag. Moreover, this technique could be also attractive because it does not make use of chemicals and, moreover, guarantees very low cost of both installation and management. Indeed, the cost of suitable cutting plotter is less than 1000 USD and the only necessary consumables are the adhesive copper sheets, costing less than 5 USD each for the A4 format.

Finally, for the CP_FACS prototyping process, the achievable resolution mainly depends on two different factors. The first one is the cutting plotter resolution, which is around 250 μm also for entry level machines. The second one is the fragility of the copper. Indeed, once the antenna shape has been incised, the elimination of the extra copper becomes a crucial operation if lines 250 μm large are used. No problem have been experienced with very simple antennas requiring 500 μm of resolution, whilst for very complicated antenna shapes, lines larger than 1 mm should be preferred.



(a) (b)

(c)

Figure 3. Layouts of the three studied tag antennas: (a) narrowband folded dipole, (b) narrowband meandered dipole, and (c) wideband meandered bow-tie. Dimensional parameter varies according to the prototyping method.

3. DESIGN AND REALIZATION OF UHF RFID TAGS FOR THE EVALUATION OF THE PROTOTYPING TECHNIQUES

In this section some types of UHF RFID tags, suitable for the evaluation of the main properties of above described PL_RPCB, SI_FPCB, and CP_FACS prototyping techniques are designed. More in detail, in order to achieve an exhaustive electromagnetic characterization of the methods, three different tag antenna samples based on some of the most popular tag design techniques (such as folded dipole, meander-line and capacitive-tip loading) [43], have been selected, simulated and realized.

Before illustrating the antenna details, it is worth clarifying that, without loss of generality, FR4 (thickness 800 µm; $\varepsilon_r = 3.7$), polyamide (thickness 35 µm; $\varepsilon_r = 2.6$) and paper (thickness 35 µm; $\varepsilon_r = 1.8$) have been used as substrates for PL_RPCB, SI_FPCB, and CP_FACS approaches respectively. When such substrates are numerically modeled for simulation purposes, the extreme thinness of polyamide and paper layers does not significantly affect the antenna parameters, as exhaustively verified.

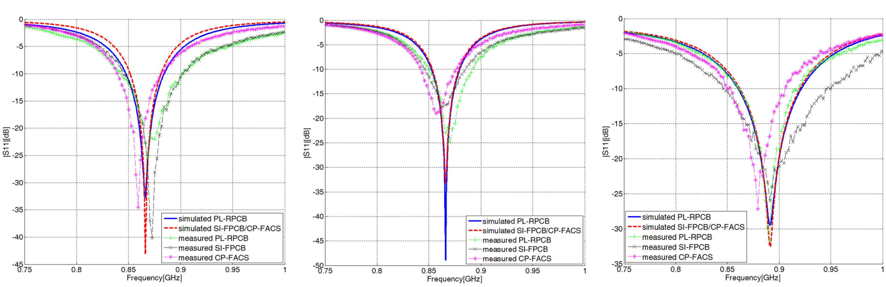
In Figure 3, the three proposed tag antenna layouts are illustrated. The first one is a simple narrowband folded dipole working in European dedicated RFID band (865–868 MHz). Vice versa, the second layout is referred to a slightly more complicated narrowband antenna, based on meander-line technique. This model of antenna has been selected since it is representative of a large class of popular tags which make use of meandered lines. Finally, the last one is an example of meandered bow-tie wideband antenna designed to work in both UE and USA RFID band (865–928 MHz), so to evaluate the appropriateness of the prototyping methods also in a wide range of frequencies. Three different sets of the proposed antennas, properly optimized for PL_RPCB, SI_FPCB and CP_FACS techniques respectively, have been simulated through the full wave simulator CST Microwave Studio®.

Table 1. Optimized antenna parameters.

	Folded Dip.		Meander-line			Bow-tie			
Parameters [mm]	L_{a1}	L_{a1}	L_{b1}	L_{b2}	L_{b3}	L_{c1}	L_{c2}	L_{c3}	L_{c4}
PL_RPCB	13.0	20.8	15.0	23.0	17.0	9.0	9.0	7.0	27.8
SI_FPCB /CP_FACS	20.0	32.0	20.0	26.0	24.9	10.1	13.0	8.0	26.7

In order to design high-performance RFID tags, as well known, a good conjugate impedance matching between tag antenna and RFID chip is necessary. In this case all the designed antennas have been carefully matched to the Impinj Monza 3 chip [44] having a measured input impedance equal to $Z_{chip\_UE} = 31\text{-}j157\Omega@866\,\text{MHz}$ (central frequency in the UE band) and $Z_{chip\_USA} = 32\text{-}j165\Omega@915\,\text{MHz}$ (central frequency in the USA band). On such basis the L_{ij} antenna parameters shown in Figure 3 have been opportunely optimized, and results for each set of considered antennas are summarized in Table 1. It is worth noting from Table 1 that exactly the same antenna parameters have been found for SI_FPCB and CP_FACS techniques, and that, vice versa, they are appreciably different from those referred to PL_RPCB. This was expected and it is substantially due to the similarity in terms of substrate thickness and permittivity in the two proposed approaches, whilst the impact of FR4 substrates in PL_RPCB is appreciable. The corresponding simulated $|S_{11}|$ curves are reported in Figure 4 where the continuous line is referred to PL_RPCB and the dashed line to both SI_FPCB and CP_FACS as they share the same simulation results. It is apparent from the graphs that, as desired, both folded dipole and meandered dipole tags are correctly sized for UE RFID band as simulated $|S_{11}|$ is, in both cases, below -40 dB around 866 MHz. Moreover, the wideband behavior of Bow-tie antennas is clearly appreciable in Figure 4(c) where the -10 dB band is large enough to include both UE and USA standards.

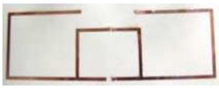
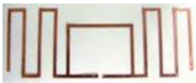
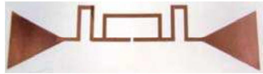
Once completed the simulation and optimization phases, all antennas have been manufactured by following PL_RPCB, SI_FPCB and CP_FACS procedures. For the sake of clarity, photos of the nine obtained prototypes have been organized in Table 2 where rows are referred to the used techniques and columns to the antenna layouts.



(a) (b) (c)

Figure 4. Simulated and measured $|S_{11}|$ of the three studied tag antenna types: (a) narrowband folded dipole, (b) narrowband meandered dipole, and (c) wideband meandered bow-tie.

Table 2. Realized tag antenna prototypes.

Tag type / Technique	Folded Dipole	Meandered Dipole	Bow-tie Dipole
PL_RPCB			
SI_FPCB			
CP_FACS			

In the next section, the measurement techniques adopted for the characterization of the antennas of Table 2 will be briefly described.

4. EXPERIMENTAL SETUPS FOR THE MEASUREMENT OF SIGNIFICANT METRICS OF PASSIVE UHF RFID TAGS

In order to measure the performance of the several prototyped tags and to compare them, two different metrics have been selected. The first one is the impedance of the tag antennas, measured before soldering the RFID chips. The second metric characterizes the assembled tags (e.g. antenna with soldered chip) and is called tag sensitivity.

Both metrics require specific measurement setups, which will be concisely described in the following subsections.

4.1. Measurement Setup for RFID Tag Antenna Impedance

All the realized passive RFID tag antennas are balanced loads, whose impedance, as well known, cannot be directly measured by directly connecting the antenna to one port of a Vector Network Analyzer (VNA). In fact, the port of a VNA is an asymmetrical port, and when a balanced antenna is connected to such a port, the currents will not be equal and opposite, because some current flows on the outside of the outer conductor, and consequently the antenna impedance results different from what expected.

To overcome such a limitation, the method firstly proposed in [45] and rigorously validated in the RFID context in [46] is applied. It is

Figure 5. The two-port probe used to measure the input impedance of the tags under test.

based on the use of an ad-hoc 2-port probe suitable for the broadband evaluation of both common mode and differential mode impedances of balanced loads and, consequently, of the searched input impedance. The photo of the two-port probe used in this paper is represented in Figure 5. It substantially consists of two identical coaxial cables having the outer conductors soldered together. The inner conductors represent the terminals to contact the antenna input. In such a way, the probe is balanced and correctly drives the antenna. Nevertheless, a particular procedure must be adopted in order to de-embed the probe contribution from the measured values. More specifically, the procedure consists of different steps. Firstly the probe is connected to the two ports of a VNA and the probe parameters are evaluated by means of short-circuit measurements. Then, the antenna is connected to the probe, so that the 2-port scattering parameter of the couple probe-antenna are measured. Afterwards, the contribution of the probe is de-embedded, the antenna scattering parameters obtained and its input impedance derived.

4.2. Measurement Setup for RFID Tag Sensitivity

Besides the antenna impedance, the performance of the assembled tag must be measured as well and a suitable metric which takes into account all the crucial aspects in defining the tag quality — the chip and its sensitivity, the tag antenna shape, and finally the goodness of the conjugate impedance matching between them — should be considered. As demonstrated in [47–49], a very appropriate parameter is the tag sensitivity. More specifically, such Tag sensitivity $S_{TH,tag}$ has been defined as the ratio between the RFID chip sensitivity $S_{TH,chip}$ and the factor $G_{tag}(1-|\Gamma|^2)$, where G_{tag} and $|\Gamma|^2$ are the gain and the power reflection coefficient of the tag antenna. In the same bibliography, $S_{TH,tag}$ as a function of $S_{TH,chip}$ has also been obtained. In fact, as $S_{TH,chip}$ is the minimum power at the chip terminal capable to switch on the chip circuitry, it can be derived from the Friis formula:

$$S_{TH,chip} = EIRP_{ON} G_{tag} \left(1 - |\Gamma|^2\right) \left(\frac{\lambda}{4\pi d}\right)^2 \eta_{plf} \tag{1}$$

where $EIRP_{ON}$ is minimum equivalent isotropically radiated power by the reader required to communicate with the tag, λ the wavelength, d the distance between tag and reader antenna, and η_{plf} the polarization loss factor.

Consequently, the tag sensitivity can be evaluated as:

$$S_{TH,tag} = \frac{S_{TH,chip}}{G_{tag}\left(1 - |\Gamma|^2\right)} = EIRP_{ON} \left(\frac{\lambda}{4\pi d}\right)^2 \eta_{plf} \tag{2}$$

It can be observed that the rigorous measurement of $EIRP_{ON}$ assures the $S_{TH,tag}$ estimation.

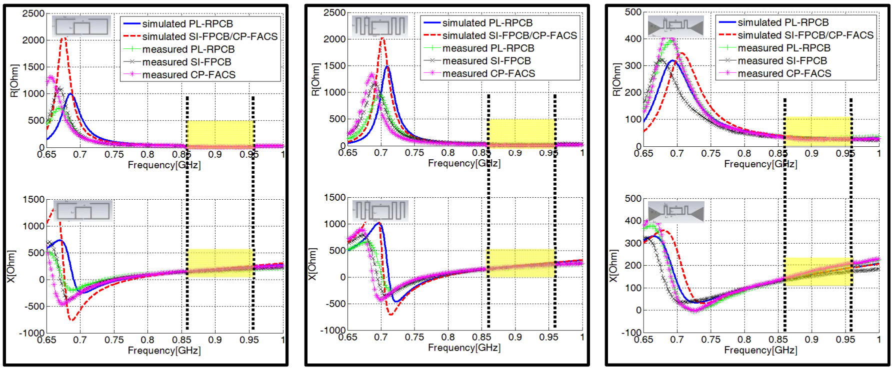
An experimental setup based on the cheap and flexible Software-Defined Radio (SDR) tool introduced in [38] is used in an anechoic environment to determine $EIRP_{ON}$ at different frequencies in the 860–960 MHz band with 1 MHz step. Successively, the tag sensitivity can be coherently calculated by (2), with the appropriate values of d and η_{plf} (in the used setup, d is set to 0.6 meters and η_{plf} to 0.5, due to the circularly polarized antennas used to interrogate the tags).

In the next section, all the prototyped antennas of Table 2 will be deeply tested by means of the above described measurement methods, in order to evaluate advantages/disadvantages of all considered prototyping techniques.

5. VALIDATION RESULTS

In this Section, in order to classify PL_RPCB, SI_FPCB, and CP_FACS prototyping methods and to allow a fair comparison among them, the three groups of three tags designed and realized in Section 3, are exhaustively characterized and compared. Specifically, several measurements of tag antenna impedance and tag sensitivity have been carried out in the whole UHF range (860–960 MHz), and results compared. A significant selection of such results is summarized below.

The first shown results are referred to the comparison between the antenna impedances simulated through CST Microwave Studio® and



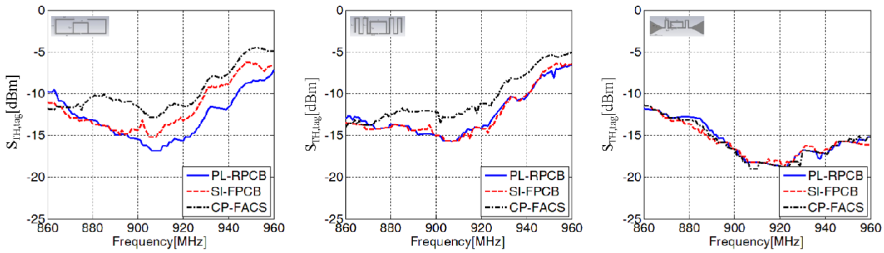
(a) (b) (c)

Figure 6. Comparison between simulated and measured tag antenna impedance by varying the prototyping method for the three studied antenna layouts: (a) folded dipole, (b) meandered dipole, and (c) meandered bow-tie. The UHF RFID investigated bandwidth is highlighted.

the ones measured through the rigorous experimental setup described in [45] and briefly recalled in Section 4.1. Such a comparison is quite relevant, because the degree of adherence between simulated and experimental data is also a measure of the capability to accurately model a tag to be realized with a specific technique and, consequently, of the ability to predict and govern its properties.

In Figure 6(a), for instance, both the real and imaginary part of the impedance of the folded dipole antenna are reported. More specifically, the two simulated results — one for the PL_RPCB case and one valid for both SI_FPCB and CP_FACS alternative approaches — are compared with experimental data. In the already observed Figure 4(a), the same results of Figure 6(a) are post-processed and shown in terms of $|S_{11}|$, for an easier and more familiar consultation. The very good agreement among results in the RFID UHF band (highlighted in the figure) demonstrates that none of the prototyping methods substantially affects the expected antenna properties, at least for the considered very simple tag shape. In addition, results shown in Figures 6(b) and 6(c), other than the calculated $|S_{11}|$ of Figures 4(b) and 4(c), confirm such a corollary also for the two and more complex cases of the meandered dipole and meandered bow-tie.

Although rather useful, the comparison between simulated and measured antenna impedance, if singularly considered, is not totally adequate for a rigorous classification of prototyping methods. For



(a) (b) (c)

Figure 7. Comparison between measured tag sensitivity by varying the prototyping method for the three studied antenna layouts: (a) folded dipole, (b) meandered dipole, and (c) meandered bowtie.

instance, antenna impedance does not take into account the RFID chip and the possible effects of the soldering. As previously argued, a particularly suitable metric is the sensitivity of the whole tag, firstly introduced in [47] and concisely described in Section 4.2 along with the testing platform and the experimental setup for its measurement.

To measure such a tag sensitivity, an exhaustive measurement campaign has been performed. In order to achieve an extensive performance comparison, the sensitivity of all the tags under test, including narrowband ones, has been measured in the whole 860–960 MHz band. Moreover, the RFID reader antennas used in the measurement set-up have been opportunely characterized [50–52].

In Figure 7(a), for instance, the tag sensitivity of the folded-dipole tag prototyped through the three different techniques is reported. As explained in Section 3, this is a narrowband tag optimized for UE RFID bandwidth. In such a range, (865–867 MHz), it can be observed that the sensitivity of all prototypes is substantially the same. For higher frequencies, some minor differences can be observed. More specifically, the cutting plotter-based tag still works also in the USA band (902–928 MHz) and performance decreases radically in the Japanese one (952–954 MHz). The same behavior is recorded for the other two techniques, but even better sensitivity values in the USA band are recorded.

Similar considerations can be done for the tag sensitivity of the three narrowband meandered dipoles reported in Figure 7(b). Also in this case all tags work fine and with similar performance in the desired bandwidth, with negligible differences elsewhere. Finally, results for the wideband case of Figure 7(c) are impressive. The three curves substantially collapse in the same graph. Even with the chip soldered on the tag antenna, no substantial differences can be appreciated among tags under test. Moreover, it is worth observing that very good sensitivity values, under −10 dBm, are measured in the whole investigated bandwidth, including the Japanese one, not considered in the simulation. It is not surprising at all. The very good sensitivity of the used chip (−15 dBm) facilitates the chip energization, so that good performance in frequency ranges larger than those expected can be achieved.

6. COMMENTS

Results presented in Section 5 deserve detailed and deeper comments. First of all, regardless the prototyping method, tags with the same layout guarantee essentially the same performance. Consequently, the individuation of the most convenient prototyping approach for a specific case should rest on other elements. The most significant one is undoubtedly the property of rigidity/flexibility that the tag should satisfy according to the application context. But also the cost, the processing time, and the physical robustness should be taken into great account.

Most of the times, the tag design is thought for a final flexible device and of course one of the two alternative approaches, SI_FPCB or CP_FACS, is strongly recommended. The choice, as stated in the previous paragraph, should be motivated by requirements different from performance. For instance, to reduce costs and shorten processing time, CP_FACS is a good choice. When physical robustness is crucial, SI_FPCB has to be preferred. Vice versa, whenever rigidity is required for the definitive prototype, only the PL_RPCB traditional approach can be adopted.

Another distinction must be done on the basis of the realization type, definitive or intermediate. Indeed, after the simulation phase and just before the definitive prototyped tag, it could be necessary to realize intermediate tag samples, whose characterization will be the feedback for potential re-optimizations. Of course, requirements to be satisfied by intermediate tag samples are mostly related to cost-effectiveness and rapidity and may differ from the definitive tag desiderata.

For flexible tag realizations, regardless the desired properties for the final device, intermediate samples can be indifferently prototyped through both CP_FACS and SI_FPCB approaches. Indeed, as discussed in Section 3, the very thin substrate made of polyamide, in one case, or paper, in the other, does not affect the simulation results so that, in both cases, the same antenna dimensional parameters are obtained from the simulation. On the contrary, when rigidity is required, not only the definitive tag prototype, but even the possible intermediate realizations, have to be carried out through the same lengthy and articulated PL_RPCB technique. Indeed, differently from SI_FPCB and CP_FACS methods, the thick substrate affects the tag properties with consequent impact on the value of each dimensional parameter of the tag antenna, as stated in Section 3 and shown in Table 1. Hence, in this case, the use of faster prototyping techniques such as CP_FACS and SI_FPCB is practically useless even in intermediate steps.

7. CONCLUSIONS

The process that brings to a new passive UHF RFID tag may require the realization of numerous samples. In fact, it starts from an idea and continues with full wave simulations. Then it passes through one or more intermediate realizations and, finally, ends up with the ultimate tag prototype. Besides this potential large number of realizations, prototyping systems commonly adopted in most of the electromagnetic labs, involved in RFID tag design, are inherited from other activities and are usually based on rigid Printed Circuit Boards (PCBs) shaped through photolithography. Apart from being articulated and time-consuming (almost one hour is needed to realize a tag sample), this last technique is also not totally appropriate for the addressed purpose, as it produces rigid instead of flexible tags.

In this work, two alternative prototyping techniques have been presented. Thanks to the joint use of flexible PCBs and a wax-based solid ink printer, the first proposed method produces flexible and physically robust tags in less than 30 minutes, making use, de facto, only of the last step of the photolithography process (chemical exposure to ferric chloride). The second method, simple but very effective, is even much more rapid: it takes only 5 minutes including RFID chip soldering. It consists of engraving the tag shape on adhesive copper sheets through a numerical control cutting plotter, and of removing the extra copper manually. Such a technique guarantees the desired tag flexibility and it is extremely cost-effective. As for the physical robustness of the realized tags, it is certainly satisfactory even though it is worst than the other two considered techniques.

In order to investigate the quality of tags realized by means of these three approaches, an exhaustive measurement campaign has been presented. Firstly, three tag layouts have been selected and full wave simulations carried out taking into account the characteristics of each prototyping method. Layouts differ from one another in terms of both adopted design technique — folded dipole, meandered dipole and meandered bow-tie, respectively — and working frequencies. Then, each tag type has been realized through both traditional and proposed alternative processes, and a comparison in terms of tag antenna impedance as well as tag sensitivity has been performed. Results are impressive. In spite of a greater simplicity, rapidity and cost-effectiveness, the two proposed prototyping methods generate label-type tags with performance as good as the rigid photolithography-based ones. Case by case, physical robustness, cost, processing time and simplicity, rather than tag performance, will dictate the most appropriate prototyping choice, as exhaustively commented in the paper.

REFERENCES

1. Chen, S.-L., S.-K. Kuo, and C.-T. Lin, "A metallic RFID tag design for steel-bar and wire-rod management application in the steel industry," *Progress In Electromagnetics Research*, Vol. 91, 195–212, 2009.
2. Kwon, H. and B. Lee, "Compact slotted planar inverted-F RFID tag mountable on metallic objects," *Electron. Lett.*, Vol. 41, No. 24, 1308–1310, 2005.
3. Yu, B., S. J. Kim, B. Jung, F. J. Harackiewicz, and B. Lee, "RFID tag antenna using two-shorted microstrip patches mountable on metallic objects," *Microwave and Optical Technology Letters*, Vol. 49, No. 2, 414–416, 2007.
4. Catarinucci, L., R. Colella, M. De Blasi, L. Patrono, and L. Tarricone, "Enhanced UHF RFID tag for drug tracing," *Journal of Medical Systems (JOMS)*, Springer, 2011.
5. Catarinucci, L., R. Colella, M. De Blasi, L. Patrono, and L. Tarricone, "Experimental performance evaluation of passive UHF RFID tags in electromagnetically critical supply chains," *Journal of Communications Software and Systems*, Vol. 7, No. 2, 59–70, 2011.
6. Catarinucci, L., R. Colella, M. De Blasi, L. Patrono, and L. Tarricone, "Improving item-level tracing systems through Ad Hoc UHF RFID tags," *Proc. IEEE Radio and Wireless Symposium, RWW 2010*, 160–163, 2010.
7. Vaz, A., A. Ubarretxena, I. Zalbide, D. Pardo, H. Solar, A. Garcia-Alonso, and R. Berenguer, "Full passive UHF tag with a temperature sensor suitable for human body temperature monitoring," *IEEE Trans. Circuits Syst. II*, Vol. 57, No. 2, 95–99, Feb. 2010.
8. Occhiuzzi, C., C. Paggi, and G. Marrocco, "Passive RFID strain-

sensor based on meander-line antennas," *IEEE Trans. Antennas Propagat.*, Vol. 59, No. 12, 4836–4840, Dec. 2011.

9. Yeager, D., P. Powledge, R. Prasad, D. Wetherall, and J. Smith, "Wirelessly-charged UHF tags for sensor data collection," *IEEE Proceeding of RFID International Conference*, 320–327, Apr. 2008.
10. Catarinucci, L., R. Colella, and L. Tarricone, "A cost-effective UHF RFID tag for transmission of generic sensor data in wireless sensor networks," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 5, Part 2, 1291–1296, 2009.
11. Esposito, A., L. Tarricone, M. Zappatore, L. Catarinucci, and R. Colella, "A framework for contextaware home-health monitoring," *International Journal of Autonomous and Adaptive Communications Systems*, Vol. 3, No. 1, 75–91, 2010.
12. Catarinucci, L., M. Cappelli, R. Colella, and L. Tarricone, "A novel low-cost multisensor-tag for RFID applications in healthcare," *Microwave and Optical Technology Letters*, Vol. 50, No. 11, 2877–2880, 2008.
13. Catarinucci, L., R. Colella, and L. Tarricone, "A new enhanced UHF RFID sensor-tag," *Proc. of the 5th European Conference on Antennas and Propagation, EUCAP 2011*, Rome, Italy, Apr. 2011.
14. Or, Y. C., K. W. Leung, R. Mittra, and K. V. S. Rao, "Analysis on the platform-tolerant radio-frequency identification tag antenna," *IET Microw. Antennas Propag.*, Vol. 3, No. 4, 601–606, 2009.
15. Catarinucci, L., R. Colella, and L. Tarricone, "Optimized antennas for enhanced RFID sensor tags," *Proc. of IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, Spokane, Washington, Jul. 2011.
16. Congedo, F., G. Monti, L. Tarricone, and M. Cannarile, "Broadband bowtie antenna for RF energy scavenging applications," *Proceedings of the 5th European Conference on Antennas and Propagation, EUCAP 2011*, 335–337, 2011.
17. Catarinucci, L., S. Tedesco, D. De Donno, and L. Tarricone, "Platform-robust passive UHF RFID tags: A case-study in robotics," *Progress In Electromagnetics Research C*, Vol. 30, 27–39, 2012.
18. Monti, G., F. Congedo, D. De Donno, and L. Tarricone, "Monopole-based rectenna for microwave energy harvesting of UHF RFID systems," *Progress In Electromagnetics Research C*, Vol. 31, 109–121, 2012.
19. Marrocco, G. and S. Caizzone, "Electromagnetic models for passive RFID tag-to-tag communications," *IEEE Transactions on*

Antennas and Propagation, 2012.

20. Monti, G., L. Tarricone, and M. Spartano, "X-band planar rectenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 1116–1119, 2011.
21. Catarinucci, L., R. Colella, and L. Tarricone, "Design, development, and performance evaluation of a compact and long-range passive UHF RFID tag," *Microwave and Optical Technology Letters*, Vol. 54, No. 5, 1335–1339, 2012.
22. Monti, G., L. Catarinucci, and L. Tarricone, "Broad-band dipole for RFID applications," *Progress In Electromagnetics Research C*, Vol. 12, 163–172, 2010.
23. Monti, G. and F. Congedo, "UHF rectenna using a bowtie antenna," *Progress In Electromagnetics Research C*, Vol. 26, 181–192, 2011.
24. Catarinucci, L., S. Tedesco, and L. Tarricone, "On the use of UHF RFID antenna systems customized for robotic applications," *Proc. IEEE International Symposium on Antennas and Propagation, APSURSI 2012*, Chicago, IL, 2012.
25. Rao, K. V. S., P. V. Nikitin, and S. F. Lam, "Antenna design for UHF RFID tags: A review and a practical application," *IEEE Trans. Antennas Propagat.*, Vol. 53, No. 12, 3870–3876, Dec. 2005.
26. De Donno, D., F. Ricciato, L. Catarinucci, A. Coluccia, and L. Tarricone, "Challenge: Towards Distributed RFID Sensing with Software-Defined Radio," *Proc. of the Annual International Conference on Mobile Computing and Networking, MOBICOM*, 97–104, Chicago, IL, 2010.
27. De Donno, D., L. Tarricone, L. Catarinucci, V. Lakafosis, and M. M. Tentzeris, "Performance enhancement of the RFID epc gen2 protocol by exploiting collision recovery," *Progress In Electromagnetics Research B*, Vol. 43, 53–72, 2012.
28. Marrocco, G., "The art of UHF RFID antenna design: Impedance-matching and size-reduction techniques," *IEEE Antennas Propag. Mag.*, Vol. 50, No. 1, 66–79, Feb. 2008.
29. Monti, G., L. Catarinucci, and L. Tarricone, "Compact microstrip antenna for RFID applications," *Progress In Electromagnetics Research Letters*, Vol. 8, 191–199, 2009.
30. Abu, M. and M. K. A. Rahim, "Triple-band printed dipole antenna for RFID," *Progress In Electromagnetics Research C*, Vol. 9, 145–153, 2009.
31. Amin, Y., Q. Chen, L.-R. Zheng, and H. Tenhunen, "Development and analysis of flexible UHF RFID antennas for "green"

electronics," *Progress In Electromagnetics Research*, Vol. 130, 1–15, 2012.

32. Yang, L., A. Rida, R. Vyas, and M. M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 12, Part 2, 2894–2901, 2007.
33. Pranonsatit, S., D. Worasawate, and P. Sritanavut, "Affordable ink-jet printed antennas for RFID applications," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 2, No. 5, 878–883, May 2012.
34. Ukkonen, L., T. Bjorninen, A. Z. Elsherbeni, and L. Sydänheimo, "Inkjet-printed humidity sensor for passive UHF RFID systems," *IEEE Transactions on Instrumentation and Measurement*, Vol. 60, No. 8, 2768–2777, 2011.
35. Allen, M. L., K. Jaakkola, K. Nummila, and H. Seppa, "Applicability of metallic nanoparticle inks in RFID applications," *IEEE Transactions on Components and Packaging Technologies*, Vol. 32, No. 2, 325–332, Jun. 2009.
36. Kim, N.-S. and K. N. Han, "Future direction of direct writing," *Journal of Applied Physics*, Vol. 108, No. 10, 102801–102806, 2010.
37. De Paolis, R., S. Pacchini, F. Coccetti, G. Monti, L. Tarricone, M. M. Tentzeris, and R. Plana, "Circuit model of carbon-nanotube inks for microelectronic and microwave tunable devices," *IEEE MTT-S International Microwave Symposium Digest*, 2011.
38. Gao, B. and M. M. F. Yuen, "Optimization of silver paste printed passive UHF RFID tags," *Proc. of International Conference on Electronic Packaging Technology & High Density Packaging, ICEPT-HDP*, 512–515, Aug. 2009.
39. Fjelstad, J., *Flexible Circuit Technology*, 3rd Edition, BNR Publishing, Seaside OR, 2006.
40. Stearns, T., *Handbook of Flexible Circuits*, McGraw-Hill, NY, 1995.
41. Abad, E., B. Mazzolai, A. Juarros, D. Gómez, A. Mondini, I. Sayhan, A. Krenkow, and T. Becker, "Investigation of fabrication and encapsulation processes for a flexible tag microlab," *Microsyst. Technol.*, Vol. 14, Nos. 4–5, 527–534, Apr. 2008.
42. Dupont Products homepage, last accessed: Apr. 2012, http://www2.dupont.com/home/en-us/index.html.
43. Dobkin, D. M., *The RF in RFID: Passive UHF RFID in Practice*, Elsevier/Newnes, 2007.

44. Impinj UHF RFID Products homepage, last accessed: Apr. 2012, http://www.impinj.com.
45. Palmer, K. D. and M. W. Rooyen, "Simple broadband measurements of balanced loads using a network analyzer," *IEEE Transactions on Instrumentation and Measurement*, Vol. 55, No. 1, 266–272, 2006.
46. Kuo, S.-K., S.-L. Chen, and C.-T. Lin, "An accurate method for impedance measurement of RFID tag antenna," *Progress In Electromagnetics Research*, Vol. 83, 93–106, 2008.
47. Catarinucci, L., D. De Donno, R. Colella, F. Ricciato, and L. Tarricone, "A cost-effective SDR platform for performance characterization of RFID tags," *IEEE Transactions on Instrumentation and Measurement*, Vol. 61, No. 4, 903–911, Apr. 2012.
48. Catarinucci, L., D. De Donno, M. Guadalupi, F. Ricciato, and L. Tarricone, "Performance analysis of passive UHF RFID tags with GNU-radio," *Proc. IEEE International Symposium on Antennas and Propagation, APSURSI 2011*, 541–544, Spokane, WA, 2011.
49. De Donno, D., L. Catarinucci, R. Colella, F. Ricciato, and L. Tarricone, "Differential RCS and sensitivity calculation of RFID tags with software-defined radio," *Proc. IEEE Radio and Wireless Symposium, RWS 2012*, 9–12, Santa Clara, CA, 2012.
50. Cataldo, A., G. Monti, E. De Benedetto, G. Cannazza, L. Tarricone, and L. Catarinucci, "Assessment of a TD-based method for characterization of antennas," *IEEE Transactions on Instrumentation and Measurement*, Vol. 58, No. 5, 1412–1419, 2009.
51. Cataldo, A., G. Monti, E. De Benedetto, G. Cannazza, L. Tarricone, and L. Catarinucci, "A comparative analysis of reflectometry methods for characterization of antennas," *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, 240–243, Victoria, BC, Canada, 2008.
52. Cataldo, A., E. De Benedetto, G. Cannazza, and G. Monti, "A reliable low-cost method for accurate characterization of antennas in time domain," *Metrology and Measurement Systems*, Vol. 15, No. 4, 571–583, 2008.