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PASSIVE UHF RFID TAGS WITH THERMAL-TRANSFER-PRINTED ANTENNAS

PASIVNE UHF-RFID-NALEPKE Z ANTENAMI ZA TERMIČNI PRENOS TISKA

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Papers for the thermal transfer printing of UHF RFID antennas were prepared by coating and calendering. Real and imaginary components of the impedance of the UHF RFID antennas depended on their design, coating composition and conditions of paper calendering. Passive UHF RFID tags were constructed from antennas and chips whose real and imaginary components of impedance in the 860–960 MHz frequency band were at approximately the same level. The communication quality of passive UHF RFID tags was evaluated by measuring the reading range using the designed UHF RFID reading unit. The reading range of experimental UHF RFID tags with printed antennas on paper and commercial UHF RFID tags with chemically etched antennas on a PET film were identical in the 860 MHz frequency.

Keywords: printed RFID antenna, tag integration, coated paper, calendaring

Avtorji v članku opisujejo pripravo papirja za termično prenašanje tiska z ultravisoko radiofrekvenčno (UHF) identifikacijo (RFID). Papir s prevleko so pripravili s postopkom kalendriranja oz. kontinuirnim valjanjem materiala v tanko folijo. Realne in imaginarne impedančne komponente UHF-RFID-anten so odvisne od njihove oblike, sestave prevleke in pogojev valjanja papirja. Pasivne UHF-RFID-nalepke so konstruirali iz anten in odrezkov, katerih realne in imaginarne impedančne komponente so približno na enakem nivoju frekvenčnega (860–960 MHz) pasu. Kakovost komunikacije pasivnih UHF-RFID-nalepk so avtorji izmerili z odčitavanjem uporabljenega območja oblikovanih UHF- RFID-enot za branje. Območje branja eksperimentalnih UHF-RFID-nalepk z antenami za termično tiskanje na papir in komercialne UHF-RFID-nalepke s kemično jedkanimi antenami na polietilen-tereftalatnem filmu (PET-filmu) so bile enake pri frekvenci 860 MHz.

Ključne besede: tiskane RFID-antene, integracija nalepk, papir s prevleko, kontinuirno valjanje (kalendriranje)

1 INTRODUCTION

Radio-frequency identification (RFID) technology allows for the identification of objects at a distance and, unlike printed symbols (such as an optical bar code), does not require direct visibility between the reading device and the monitored object. As RFID technology works on the principle of identification using electromagnetic waves, it is contactless.

At present, almost all RFID tag antennas are manufactured by the chemical etching of metal foils, or printing on plastic substrates. The production by chemical etching is expensive, uses hazardous chemicals and produces hazardous waste, and therefore is restricted in practice. Printing RFID antennas, is clean, has little or no hazardous waste, and can be practiced almost anywhere without restriction. Printing methods for antennas include screen printing, flexography, gravure, inkjet and thermal transfer. Various plastic films[1–3] or, less commonly, paper substrates[4–12] are used to print antennas.

Paper substrates are becoming preferred to plastic films for RFID antennas as they are more environmentally and economically advantageous. A major challenge to printing antennas on paper, has been to match the electrical conductance needed, which is readily obtained on plastic films. This first requires a significant reduction in the surface roughness of the paper, which is achieved by a combination of coating and calendering the paper's surface. In addition, through coating composition and quantity, not just the specific smoothness, but also desired porosity, surface energy and absorbency can be obtained. For printed electronics, paper dust must be avoided, so low dustiness is also necessary.

Thermal transfer printing with Metallograph® conductive ribbon is a simple, fast and economical method of digital printing for electronic circuits, sensors and RFID antennas.[13,14] Metallograph® ribbon, a product of IIMAK and SPF-Inc., consists of a heat-resistant coating, a carrier polyethylene terephthalate (PET) film, a release layer, a vacuum metallised continuous layer, and a thermoplastic bonding layer that bonds the metallised layer to the substrate when heated, as in the thermal transfer printer. Compared to printing techniques such as screen printing, flexography, gravure and inkjet printing, which use pastes and inks containing mostly silver nanoparticles, thermal transfer printing uses aluminum, which is about two orders of magnitude less costly for the equivalent conductivity of silver. Additionally, there are

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no fluids, no printing set up, no drying and no sintering of the silver nanoparticles. Without these additional steps the process has a very small footprint and takes less than a second to accomplish.

The biggest advantage of smart labels and packaging is a dramatic improvement in the accuracy of the inventory and item location. A smart label is an extremely flat configured tag under a conventional print-coded label, which includes chip, antenna and bonding wires as a so-called inlay. Smart packaging refers to packaging systems with embedded indicators, sensors and tags. In a retail operation, this alone produces remarkable returns on investment. Additionally, they offer product authentication, reviving the customer experience, as well as reducing manual labour, costs and errors due to inaccuracies and inefficiencies.

The aim of this work was to prepare papers for the thermal transfer printing of aluminium antennas, and identifying a complementary antenna and chip design for the production of a powerful passive UHF RFID tag.

2 EXPERIMENTAL PART

2.1 Materials

Experimental calendered and coated fine paper – EXP1 paper (Pulp and Paper Research Institute -PPRI).

Experimental calendered and coated fine thermal transfer paper – EXP3 paper (PPRI).

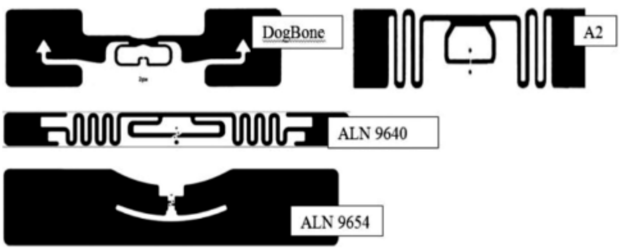

Figure 1: Designs of symmetric dipole UHF RFID antennas

Smart paper Type 1 – SP paper (Felix Schoeller Group).

Polyethylene terephthalate (PET) film – Melinex ST 505 (DuPont Teijin Films sp.).

Print templates of UHF RFID antennas – DogBone, A2, ALN 9640 and ALN 9654 (**Figure 1**).

Test kit of UHF RFID tags – ALN 9640 and ALN 9654 with chemically etched antennas on PET film and with chip Alien Higgs 3 (Codeware Ltd.).

UHF RFID chip – NXP UCODE G2iL without user memory (NXP Semiconductors).

UHF RFID chip – Alien Higgs 3 with user memory (Avery Dennison Corp.).

2.2 Methods

Coating of the base papers was performed using a Dow Chemicals laboratory knife coater (Trailing Blade system).

Calendering of papers was performed using a Kleinewefers laboratory calender by two passes between paper and metal cylinder at a linear load in the nip of 260 kN/m and a temperature of 80 °C. The coated side was in contact with the heated metal cylinder.

The surface roughness of paper was evaluated by the photoclinometric method as optical variability of surface OVS_{CLINO}.[15]

The surface porosity of the paper was evaluated by high (10000×) magnification scanning electron microscopy. The distribution of light and dark image areas obtained by scanning electron microscopy (SEM), as well as by photoclinometric method, was evaluated using ImageJ software. The optical variability of surface OVS_{SEM} is expressed as coefficient of variation of the original SEM image histogram and contains summarized information about surface pores and binder surface fractions.[16]

Printing of UHF RFID antennas on papers and PET film was performed in a SATO CL4NX thermal transfer printer (Japan) with Metallograph® ribbon (SPF-Inc., USA) containing 260 nm thick aluminium layer (**Figure 2**). Antenna DogBone and antenna A2 were printed

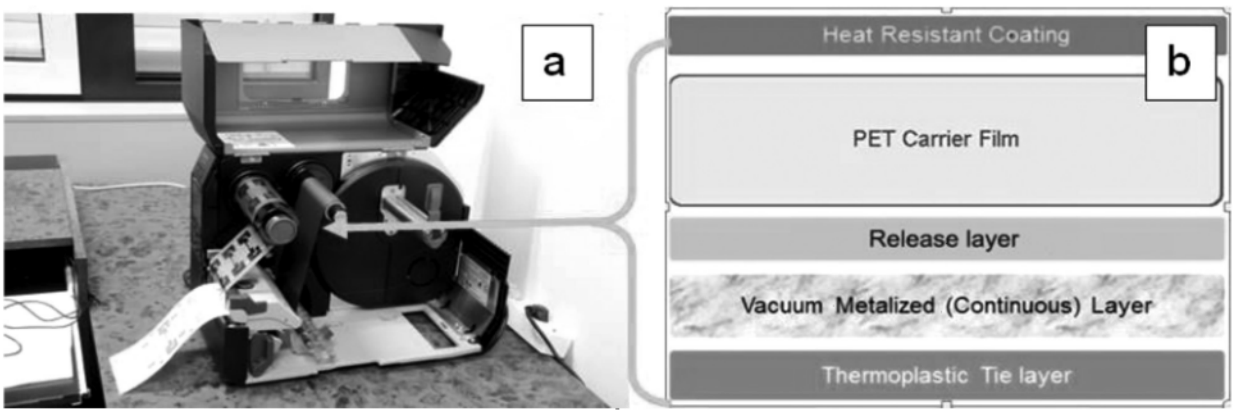

Figure 2: a) Thermal transfer printer SATO CL4NX and b) Metallograph® ribbon

on EXP1 and EXP3 experimental papers, SP paper and PET film. Antennas ALN 9640 and ALN 9654 were printed only on EXP1 experimental paper and PET film.

The antenna impedance was measured with a Network Analyzer HP 8753D. Impedance is the apparent resistance of an antenna when a harmonic alternating current passes at a given frequency. Impedance is a complex number that has its real and imaginary components:

$$Z = Z_{RE} + jZ_{IM} \quad (1)$$

The thicknesses of the aluminium antennas were determined by SEM microscopy using a JEOL JSM 6610 microscope equipped with an EDS detector X-Max 50 mm^2 (Oxford Instruments Ltd.). Antenna samples were cut, ultrasonically cleaned and observed in a microscope at various magnifications. The surface of the samples was subjected to EDX analysis in an electron microscope at a magnification of 250×.

Experimental UHF RFID tags were prepared in a manual Die Bonder & Component Placer T-3000-FC3 (Dr. Tresky AG) by gluing chips to the ends of the antennas using an anisotropic conductive, heat-curing adhesive DELO MONOPOX AC268.

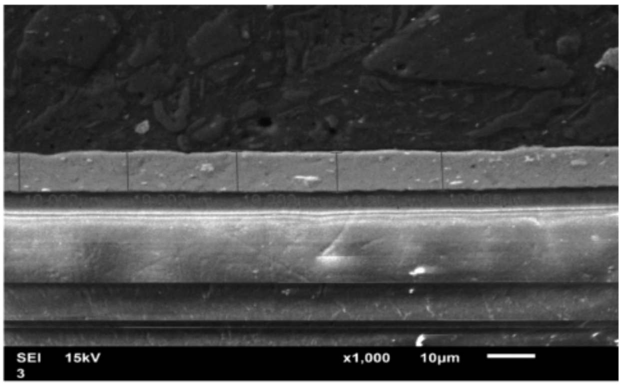

Figure 3: SEM microstructure of chemically etched aluminium antenna on PET film in cross-section with the aluminium layer shown

Reading range of passive UHF RFID tags was evaluated by a reader with antenna reader made at PPRI. The reading range is the maximum distance from which the reader is able to reliably read the response from the tag.

3 RESULTS AND DISCUSSION

3.1 Surface roughness and porosity of papers

Coating and calendering processes were used for the surface treatment of papers. The smoothness of the surface depended on the composition of coatings, the amount and layers of the coating and the surface calendering conditions. The formulation of coating compositions was based on the results of our previous works.[17–19]

In **Table 1** are the surface roughness and porosity of experimental papers EXP1 and EXP3, and commercial SP paper expressed by the optical variability of surface. The paper surface roughness of the paper of about 6 % is a necessary condition for obtaining conductive antennas.

Table 1: Surface properties of papers

Paper	Surface roughness OVS_{CLINO} (%)	Surface porosity OVS_{SEM} (%)
EXP1	5.3	33.5
EXP3	5.8	30.9
SP	6.1	6.2

3.2 Thickness of the aluminium antennas

A chemically etched aluminium antenna on a plastic UHF RFID tag is shown in cross-section using SEM microscopy in **Figure 3**. The thickness of the antenna was 10 μm. **Figure 4** is SEM microstructure of an aluminium antenna printed by thermal transfer technique on EXP3 paper in cross section. Cracking is caused by dehydration during preparation for SEM viewing. The thickness of the antenna was 260 nm. The picture on the right of

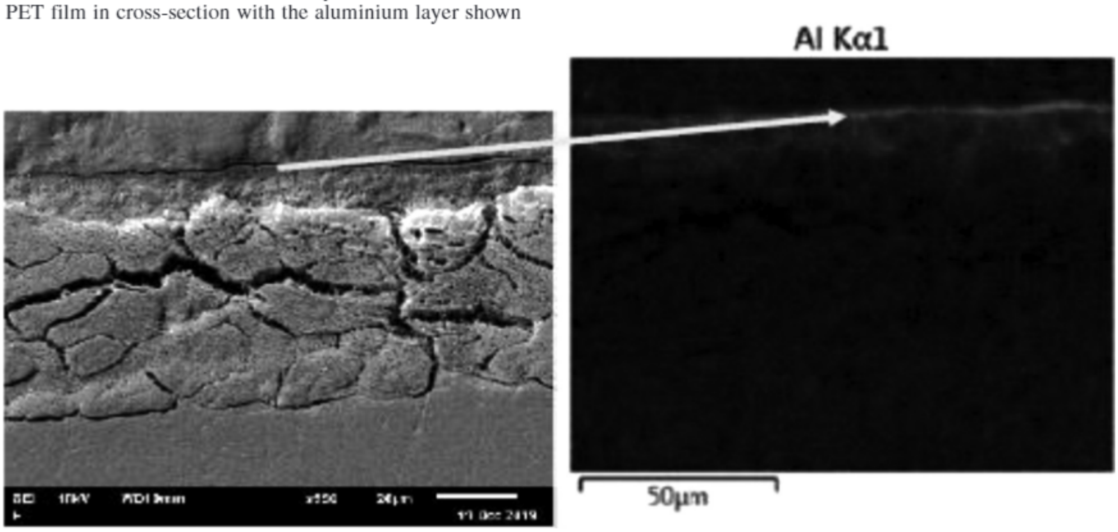

Figure 4: SEM microstructure of an aluminium antenna printed by thermal transfer technique on EXP3 paper in cross-section with the aluminium layer shown by EDS mapping

Figure 4 was made by X-ray microanalysis using EDS mapping and the red line confirms the aluminium layer.

3.3 Impedance of aluminium antennas

The UHF RFID antenna must be designed and printed on the substrate so that it can be connected to a UHF RFID chip and to meet the transmitted power requirements when using a tag. Most tag antennas on the market are dipole antennas, which allow communication between the reader and the tag over long distances. The dipole shape of the antenna provides the best UHF signal propagation in the frequency band 860 MHz to 960 MHz. For the realization of the maximum energy transfer the antenna impedance of the tag Z^{ant} should be adjusted to the impedance of the chip Z^{chip} according to Equation (2):

$$Z^{ant} = Z^{ant}_{RE} + jZ^{ant}_{IM} = Z^{chip}_{RE} - jZ^{chip}_{IM} = Z^{chip} \quad (2)$$

Changes of the real and imaginary components of the impedance of two types of dipole UHF RFID aluminum antenna DogBone and antenna A2 (**Figure 1**) printed by the thermal transfer method were measured in the frequency range 700–1000 MHz. The values of the real component Z^{ant}_{RE} and the imaginary component Z^{ant}_{IM} of the impedance of the aluminium antenna DogBone printed on papers and PET film for the frequencies 864 MHz, 915 MHz and 953 MHz are presented in **Table 2**. The real impedance components of the DogBone antenna at 864 MHz on the papers were in the range of 44–54 Ω and on PET film 35 Ω.

Table 2: Values of real and imaginary components of impedance of aluminum DogBone antenna printed on papers and PET film

Frequency	864 MHz		915 MHz		953 MHz	
Regional operation	Europe		USA		Asia	
Impedance (Ω)	Z_{RE}	Z_{IM}	Z_{RE}	Z_{IM}	Z_{RE}	Z_{IM}
PET film	35	+j136	35	+j144	35	+j151
EXP1 paper	54	+j140	45	+j146	40	+j154
EXP3 paper	47	+j127	43.5	+j136	36	+j145
SP paper	44	+j132	38	+j156	35	+j145

The values of the real component Z^{ant}_{RE} and the imaginary component Z^{ant}_{IM} of the impedance of the aluminium antenna A2 printed on the same substrates for the frequencies used in Europe, USA and Asia are given in **Table 3**. The real components of the impedance of antenna A2 at the frequency of 864 MHz were on papers 22–23 Ω and on PET film 18 Ω.

Table 3: Values of real and imaginary components of impedance of aluminium A2 antenna printed on papers and PET film

Frequency	864 MHz		915 MHz		953 MHz	
Regional operation	Europe		USA		Asia	
Impedance (Ω)	Z_{RE}	Z_{IM}	Z_{RE}	Z_{IM}	Z_{RE}	Z_{IM}
PET film	18	+j104	20.3	+j122	20.5	+j129
EXP1 paper	23	+j115	21.5	+j125	21.5	+j134
EXP3 paper	22	+j101	20.3	+j119	19.7	+j126
SP paper	23	+j103	21.5	+j122	21.5	+j131

The results of impedance measurements of UHF RFID aluminium antennas DogBone and A2 printed on experimental EXP1 and EXP3 papers, commercial SP paper and PET film showed that the influence of antenna design and substrate type on the real and imaginary component of impedance was significant.

3.4 Reading range of experimental passive UHF RFID tags

The communication quality of the experimental passive tags with the antenna printed on paper and the chemically etched antenna on PET film was assessed by measuring the distance of the UHF RFID tag from the reader antenna needed to identify the Electronic Product Code (EPC) and read the fixed data in the chip. The same chip and the same antenna design were used in both cases to compare the results. Tag **1** consisted of a DogBone antenna printed on experimental paper EXP1, connected to a chip NXP UCODE G2iL. Tag **2** consisted of a chemically etched DogBone antenna on PET film connected to a chip NXP UCODE G2iL. The reading ranges of both passive UHF RFID tags are given in **Table 4**. Reading range of the EPC of passive UHF RFID tag 1 and tag 2 was 4.1 m, respectively 4.0 m and reading range of fixed data was 3.5 m, respectively 3.6 m.

Table 4: Comparison of reading range of experimental passive UHF RFID tags

Passive UHF RFID tag	1	2
Substrate	EXP1 paper	PET film
Antenna design	DogBone	DogBone
Antenna production	Thermal transfer printing	Chemical etching
Antenna thickness (μm)	0.26	10
Chip	NXP UCODE G2iL	NXP UCODE G2iL
Reading range of EPC (m)	4.1	4.0
Reading range of fixed data (m)	3.5	3.6

The reading range depends on the threshold sensitivity of RFID chips, which is given in dBm. This unit indicates the power ratio in decibels per 1 mW of power. The values of the real and imaginary components of the impedance and the sensitivity of some readily available UHF RFID chips are presented in **Table 5**. As the real component of the chip impedance decreases, the power consumption of the reader decreases and the sensitivity of the chip increases. The chips NXP UCODE 7 and UCODE 8, Impinj Monza 6 and Alien Higgs-EC had the highest sensitivity for reading and recording.

For optimal power transmission, the impedance of the tag antenna Z^{ant} must be matched to the impedance of the chip Z^{chip} according to Equation (2). To increase the reading range of the tag with the DogBone antenna, it will be more appropriate instead of the chip NXP UCODE G2iL to use the chip Impinj Monza 2

Table 5: Values of real and imaginary components of impedance and sensitivity of UHF RFID chips Characteristics of chips NXP UCODE, Impinj Monza and Alien Higgs-EC are from data sheets of producers.

Frequency	864 MHz		915 MHz		953 MHz		Chip sensitivity (dBm)	
Regional operation	Europe		USA		Asia		Reading	Recording
Impedancy (Ω)	Z_{RE}	Z_{IM}	Z_{RE}	Z_{IM}	Z_{RE}	Z_{IM}		
NXP UCODE G2iL	25	–j237	23	–j224	21	-j216	-18	
NXP UCODE 7	14.5	–j293	12.5	–j277	12.5	-j267	-21	-16
NXP UCODE 8	15	–j265	14	–j252	13	-j234	-23	-18
Impinj Monza 2	58	–j166	52	–j158	48	-j233	-17	-12
Impinj Monza 3	32	–j228	32	–j216	32	-j207	-15	-11
Impinj Monza 6							–21	–16
Alien Higgs 3[20]	30.5	–j211					–14	–11
Alien Higgs 4[21]	20.5	–j191					–19	
Alien Higgs-EC							–22.5	–19

(Z^{chip} = 58 – j166), which has similar values of the real and imaginary components of impedance (**Table 5**) as the DogBone antenna on EXP1 paper (Z^{ant} = 54 +j140), as shown in **Table 2**.

We assume that the NXP UCODE G2iL (Z^{chip} = 25 – j237) or Alien Higgs 4 (Z^{chip} = 20.5 – j191) chip would be suitable for the A2 antenna, because they have impedances at a frequency of 864 MHz close to this antenna (**Table 5**) printed on papers (Z^{ant} = [22–23] +j[101–115]), as presented in **Table 3**.

To realize the optimal energy transfer and achieve the reading range of the UHF RFID tag, suitable for a specific application in practice, the procedure is as follows: the tag chip is first selected and the tag antenna design is selected and then verified by measurement, which will be impedance adjusted to the tag chip at a specified frequency.

The reading range of experimental tag with thermal transfer printed antenna on paper substrate was the same as for a commercial tag with chemically etched antenna on a PET film. It follows that tags with thermal transfer printed antennas on paper substrates can replace tags with chemically etched antennas on PET film.

3.5 Comparison of experimental passive UHF RFID tags with test PET tags

In this section, the reading ranges of experimental tags with antennas ALN 9640 and ALN 9654 printed on experimental paper EXP1, and commercial test tags with chemically etched antennas on PET film, which contained the same Alien Higgs 3 chip, were evaluated. Unlike the chip NXP UCODE G2iL, the chip Alien Higgs 3 also has user memory, so in addition to the range for EPC identification and fixed data reading, it was possible to record and overwrite our own text.

The differences in identification, reading and recording range between the experimental and test ALN 9640 and ALN 9654 tags were insignificant from a practical point of view. In **Figure 5** are the results of measuring the range of EPC identification, reading and recording into the user memory of the UHF RFID chip of the experimental and test tags ALN 9654. The experimental tag is marked with the symbol "Paper" (green columns) and the test tag with symbol "PET" (red columns). The range of EPC identification was 3.6 m for the experimental tag, and 4.0 m for test tag. The reading range was 3.3 m for experimental tag and 3.6 m for test tag. The recording range was even lower, at 3.1 m for experimental tag and test tag.

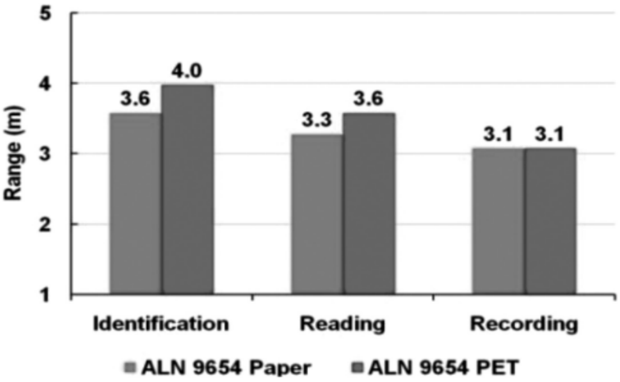

Figure 5: Identification, reading and recording range of passive tags ALN 9654 on paper and PET film

From the point of view the reading range given in **Table 4** and **Figure 5**, no significant differences were observed between the passive UHF RFID tags with antennas printed on paper and tags with chemically etched antennas on PET film, while the printed antennas are 40 times thinner.

4 CONCLUSIONS

Experimental papers EXP1 and EXP3 prepared by coating and calendering met the requirements for thermal transfer printing of aluminium UHF RFID antennas. The impedance of the antennas was significantly affected by the design, coating composition and paper calendering conditions.

Based on the compliance of the real and imaginary components of the impedance of chips and printed antennas, powerful passive UHF RFID tags with good communication quality were created. Experimental tags with a printed antenna on paper had the same reading range as commercial tags with a chemically etched antenna on a PET film.

The advantage of thermal transfer printing with ribbon is its simplicity compared to either chemical etching with hazardous materials, or printing with liquid inks, which requires set up, ink thickness control, drying and sintering, all of which is one or two orders of magnitude more expensive than thermal transfer or even hot stamping.

Advantages of passive UHF RFID tags with printed antennas on paper substrates compared to plastic ones, are their recyclability, compostability and direct manufacture on a paper product, such as a label or a package.

The discussed relationship between the impedance of the antenna and the chip of the tag will be the subject of further study in relation to the communication quality of the tag.

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