A Fully Printed Passive Chipless RFID Tag for Low-Cost Mass Production

Raji Nair[1], Marvin Barahona[1], Diego Betancourt[1], Georg Schmidt[2], Maxi Bellmann[2], Daniel Höft[2], Dirk Plettemeier[3], Arved Hübler[2], and Frank Ellinger[1]

[1] Chair for Circuit Design and Network Theory, TU Dresden, Dresden, Germany, Diego.Betancourt@tu-dresden.de

[2] Institute for Print and Media Technology, TU Chemnitz, Chemnitz, Germany, Georg.Schmidt@mb.tu-chemnitz.de

[3] Chair for RF Engineering, TU Dresden, Dresden, Germany.

Abstract— **In this paper a 3 bit chipless RFID tag able to be printed using mass production techniques is introduced. The structure proposed is based on dipole like structures and three of such dipoles conforms a tag. Several chipless RFID tag prototypes were fabricated on PET substrate and measured within the frequency band from 2 GHz to 5 GHz. In contrast to the already reported printed tags where inkjet printing is used, the proposed tag is fabricated using screen printing techniques which enable fast mass production of tags in a very short time with thick conductive tracks of ~10 µm. A good agreement between simulation and measurement was obtained and a reading distance up to 1 m is obtained with a transmission power of 3 dBm. The obtained results confirm the use of low cost printed tags for mass market applications.**

Index Terms— **chipless, screen-printing, RFID, backscattering, RCS, frequency shift encoding.**

I. Introduction

ONE of the most important and promising applications for RFID technology is the item-level tagging. In item-level tagging a RFID tag is attached, glued or printed on any product in market. Indeed, prospective for item-level tagging foresee that in a near future RFID tags will be present on thousands of millions of products developed for sectors like consumer-goods industry, pharmaceutical industry, postal services, manufacturing processes, package industry, among others [1].

According to expert projections, global item-level tagging business is expected to rise from about 180 million euros in 2008 to more than 6 billion euros in 2018 [2, 3]. These figures could only be achieved under the supposition of a strong decreasing in RFID tag prices that must be lower the 0.01 euro cent to make RFID technology be competitive respect to barcoding and, by this way, gain deep penetration in market [1].

In order to achieve these goals, novel technologies and techniques are starting to be studied. One of the most promising research fields is the chipless RFID technology. Specifically, there is strong interest on the printable chipless RFID tags over cheap-materials. Special attention is given also to methodology used in printing processes, since is wanted to include only those that are able to be used into industrial processes, assuring this way a feasible mass production of chipless RFID tags.

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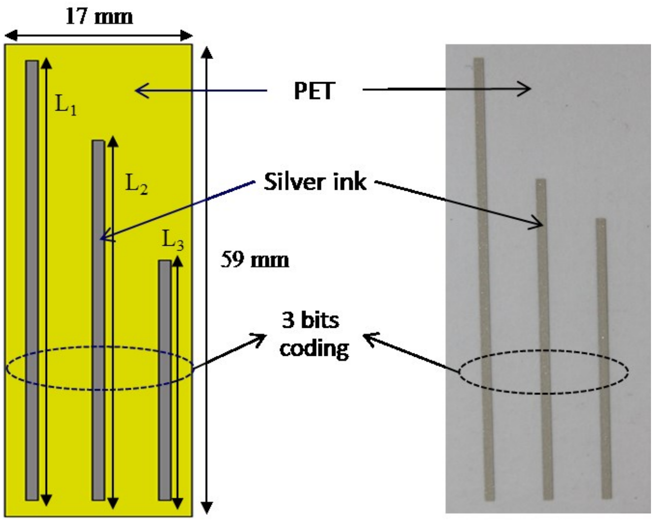

Fig. 1. Chipless RFID tag geometry. L_1=55 mm, L_2=45 mm, L_3=35 mm. Dimension of the tag is 5.9 × 1.7 cm^2. Left side: CAD model. Right side: printed prototype.

In this paper a 3 bit chipless RFID tag able to be printed using mass production techniques is introduced. The structure proposed is based on dipole like structures and three of such dipoles conforms a chipless RFID tag (See Fig. 1). Similar structures which are studied before can be seen in [4-13]. Table I summarizes the principal characteristics of these chipless tags. Designs based on dipoles are already proposed in [4-6], however, in difference to the present work, these structures need a ground plane [4, 5] and are fabricated using standard PCB techniques over FR4 [6] or Taconics [4, 5] substrates. Additionally, structure introduced in [6] is designed to be read using a closed cavity in a near field scenario. On the other hand, fully printed chipless RFID tags based on diverse geometries are reported in [7-13]. Only few works show results using PET as substrate and mass production compatible printing techniques, as is the case presented in [7] where a reading distance of 50 cm is obtained with a transmission power of 0 dBm. Chipless tags using paper as the substrate and inkjet printing techniques are shown in [8-13]. However, from Table 1 it is

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TABLE I
SUMMARY OF RELATED WORKS ON CHIPLESS RFID TAGS

Class	Geometry	Size (mm²)	Frequency (GHz)	Substrate	Substrate Thickness (µm)	Coding (bits)	Read Range (cm)	Power (dBm)	Print Technology	Ref
Frequency Domain	Dipole	59 × 19	2 to 5	PET	100	3	100	3	Screen	proposed work
		N/A	2.4, 5.25, 5.8	Taconics	800	N/A	200	27	PCB	[4]
		N/A	5.8	Taconics	800	5	N/A	N/A	PCB	[5]
		60 × 30	3 to 6	FR4	800	23	5	N/A	PCB	[6]
	C-Shape	70 × 30	2 to 8	PET, paper	120	19	50	0	Flexography, inkjet	[7]
	Split Rings	85 × 54	8.2 to 12.4	Polycarbonate	100	4	2	N/A	Inkjet	[8]
		4 × 16	12	Paper	110	2	2	N/A	Inkjet	[9]
	Spiral	5800	0.01 to 0.1	Paper	N/A	10	20	0	Inkjet	[10]
Time Domain	LC Resonator	60 × 60	0.135 to 0.33	Paper	N/A	4.25	1	0	Inkjet	[11]
	Delay Line	95 × 49	0.01 to 0.1	Paper	N/A	8	N/A	N/A	Inkjet	[12]
Other	Rhombic	70 × 40	3 to 6	Polyimide	100	6.9	20	0	Inkjet	[13]

clear that none of the printed tag except [7] could achieve a maximum reading distance greater than 50 cm. In the proposed work, several prototypes of tags were screen printed on PET and measured in an anechoic chamber. The screen printing technique enables fast mass production of tags in a very short time and also it offers thick conductive traces of ~10 µm. A reading distance of 1 m was obtained with a transmission power of 3 dBm.

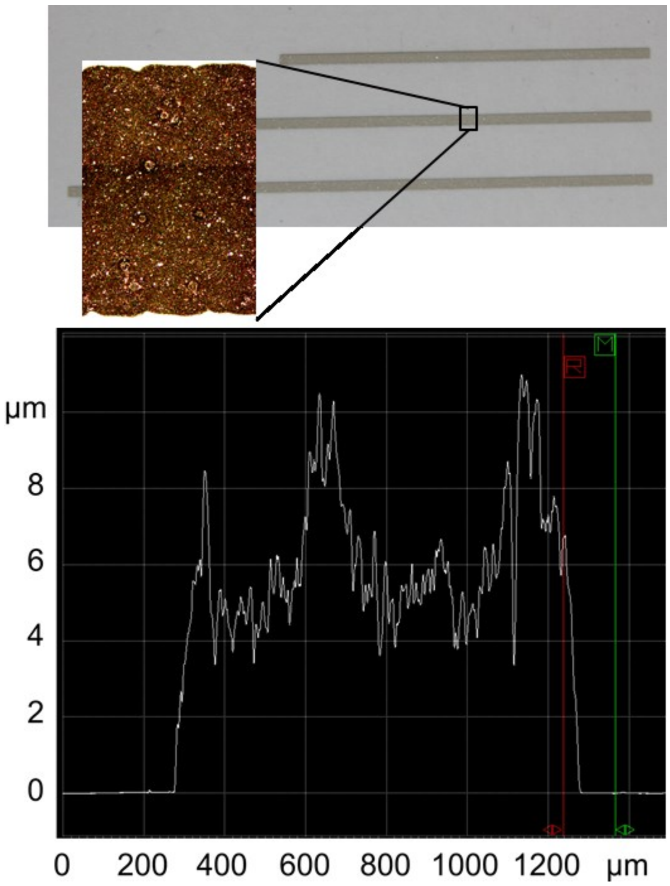

Fig. 2. Microscopic picture and profile of printed silver lines with a width of 1 mm.

II. CHIPLESS TAG PRINTING PROCESS

For the realization of the chipless RFID tags screen printing was chosen because of three main reasons: (i) screen printing is a fast mass printing technology able to produce thousands of tags in a very short time, (ii) it is an additive production technology which means that there is no waste of functional and in case of metal based inks expensive materials, and (iii) it is able to realize thick layers of up to 10 µm and more which is necessary to get low resistance of the printed structures.

For the purpose of this work the semiautomatic sheet fed screen printing system EKRA X1-SL of the Institute for Print and Media Technology at TU Chemnitz was used. Although sheetfed printing has slightly lower throughput in comparison to roll-to-roll printing technologies, which are capable for screen printing as well, it has the benefit of simpler and cheaper printing screen manufacturing.

As conductive functional material the silver based ink Dupont 5028 was chosen. This ink consists of 69-71 % silver micro particles, leading to the advantage of achieving highly conductive films without long annealing steps at high temperature like it is necessary for nano particle inks. Hence, the structures could be printed onto a conventional PET foil with a thickness of 100 µm (Dupont Teijin Films Melinex 401) [14]. To achieve a layer thickness of approx. 10 µm a screen with 280 mesh was used. After printing the structures were dried for five minutes at 130 °C in a conventional oven to remove the residual solvent. The resulting mean sheet resistance of the printed lines was in a range of 67 ± 1 mΩ/sq.

A microscopic picture of the printed silver lines taken with the help of an optical microscope is given in Fig. 2. While looking to the profile it becomes obvious that these screen printed structures are very rough, mainly due to the used micro particle ink. The mean roughness R_a was determined with the help of a profilometer Veeco Dektak 8 and measured to be 1 µm.

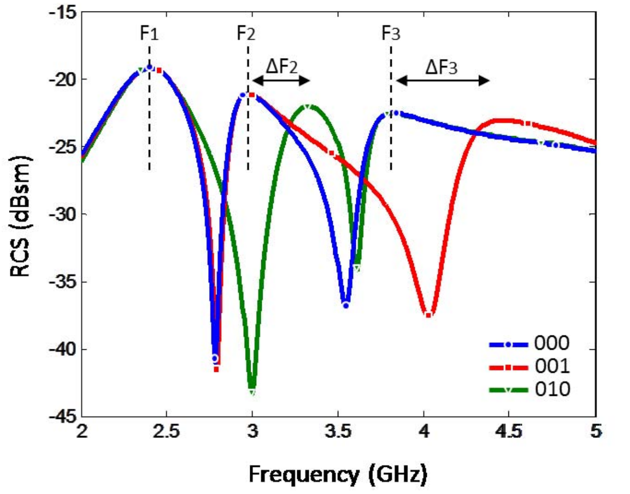

Fig. 3. Simulated RCS of the reference tag with lengths L_1=55 mm, L_2=45 mm, and L_3=35 mm; ID '000' in blue color. Frequency shifting: RCS of the tags corresponding to the IDs '001' in red and '010' in green.

III. Printed Tag Design

The proposed chipless RFID tag is based on 3 dipole like strips properly arranged at particular distances as shown in Fig. 1. Each dipole can be used to encode a single bit and hence 3 dipoles constitute 3 bits. Thus, the tag has three conductive strips which can be printed directly on a substrate. The dipoles are separated at a distance of 10 mm each other.

Each dipole is designed to resonate at a specific frequency according to the length of the strip. Antennas generally do not scatter with the same pattern that they radiate. However, in the case of dipole like structures, the radiated and scattered fields are similar [15]. Therefore, at the resonance frequency it can scatter maximum amount of power. In the same way, by varying the length of the dipole, the resonance frequency can be varied.

Simulations were performed in CST Microwave Studio using plane wave as an interrogation source (vertical polarization) and RCS (Radar Cross Section) probes were placed at a distance greater than far field distance, R, to collect the backscattered signal (RCS) of the tag. Initially, the permittivity of the substrate was chosen as 2.9 as per the data sheet (until 1 GHz) provided by the manufacturer [14]. A slight change in this value was expected in high frequencies and we observed a small shift in the measurement results and hence simulations were performed to extrapolate the value of permittivity and 3.7 were found as the value which matches with the results. The loss tangent is set as 0.0025 according to [14]. The thickness of the substrate is 100 µm and the thickness of the conductive lines is chosen as 10 µm (corresponding to the screen printing metallic trace thickness). The width of the dipole was set as 1 mm.

Due to the thickness of substrate used (100 µm) it is expected that the resonance frequencies of the chipless RFID tag will be a function of the medium behind the substrate. In this work the surrounding medium is air and it is not expected any behavior deviation between simulations and results obtained in measurements.

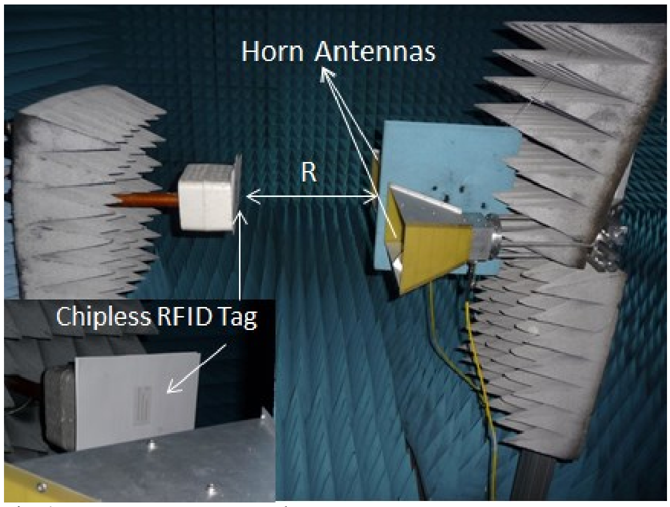

Fig. 4. Measurement set-up used.

When this tag is interrogated with a vertically polarized plane wave (similar to a reader in practical case [16]), each dipole resonates at its design frequency and as a result the magnitude of the backscattered signal will be maximum at these frequencies as shown in Fig. 3.

A. Frequency Shift Encoding

The frequency shift encoding proposed in [7] is used here which allows encoding of more than one bit per resonator. In this approach the frequency shift produced by each dipole by changing the length of each dipole with respect to the reference tag can be used for the encoding. Since three dipoles have been used in the proposed case, each dipole can produce resonances at frequencies F_1, F_2, and F_3. Each resonance can be assigned by a binary value and thus the reference tag constitutes the ID '000'. The reference tag is set to have L_1=55 mm, L_2=45 mm, and L_3=35 mm. Other tag combinations can be produced by changing the length of the dipoles.

Now imagine that the length of the second dipole has been changed. This will cause shifting of the second resonance to a frequency $F_2 \pm \Delta F_2$ keeping the other resonance frequencies constant as shown in Fig. 3. This frequency shift can be assigned by logic 1. Thus this combination can produce the ID '010'. Similarly, changing the length of third dipole will shift the third resonance to $F_3 \pm \Delta F_3$, keeping the first and second resonance constant as shown in Fig. 3 and hence constitutes the ID '001'. Thus, different tag combinations can be produced by changing the length of each dipole. As a proof of concept, only one shift per resonance is considered

TABLE II
ENCODING USING FREQUENCY SHIFTING FOR 3 BIT CHIPLESS RFID TAG

Binary code	Frequency resonances		
000	F_1	F_2	F_3
001	F_1	F_2	$F_3 \pm \Delta F_3$
010	F_1	$F_2 \pm \Delta F_2$	F_3
011	F_1	$F_2 + \Delta F_2$	$F_3 + \Delta F_3$
100	$F_1 \pm \Delta F_1$	F_2	F_3
101	$F_1 \pm \Delta F_1$	F_2	$F_3 \pm \Delta F_3$
110	$F_1 \pm \Delta F_1$	$F_2 \pm \Delta F_2$	F_3
111	$F_1 \pm \Delta F_1$	$F_2 \pm \Delta F_2$	$F_3 \pm \Delta F_3$

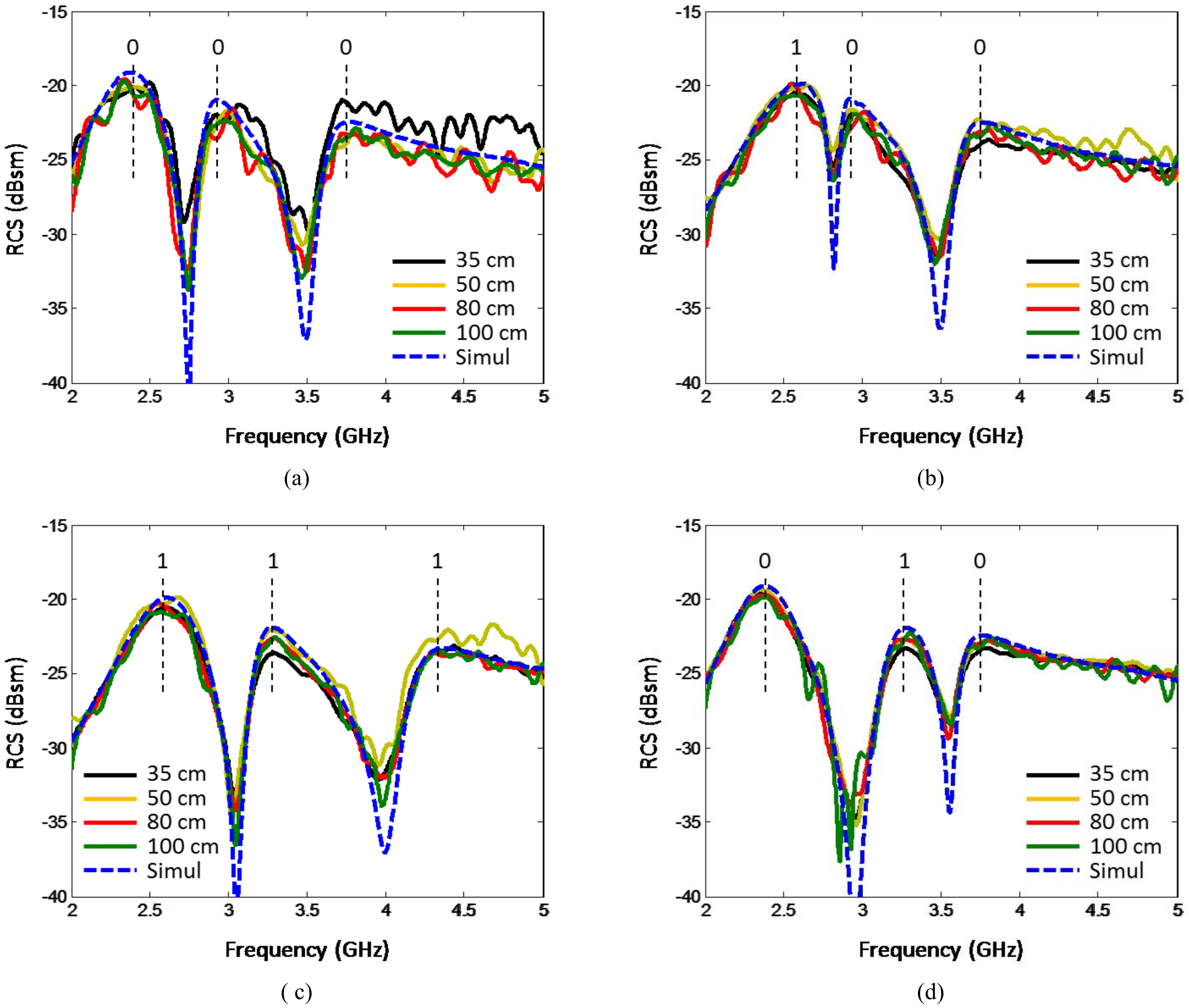

Fig. 5. Measurement results obtained for different chipless RFID tags at several distances. (a) reference tag, ID '000'; (b) tag with ID '100'; (c) tag with ID '111' and (d) tag with ID '010'.

here and hence constitutes a 3 bit code. However, coding capacity can be easily increased by considering more than one frequency shift.

Table II explains the principle of encoding (for logic ´1´; the frequency of resonance changes and for logic ´0´, the frequency of resonance remains unchanged). Thus, for the designing of chipless RFID tag, there should always be a relation between the geometry of the tag and the binary code. As explained above, the binary code can be changed simply by changing the length of each dipole, provided, each resonance peak should be independent of each other.

IV. RESULTS & DISCUSSION

The proposed designs were printed as shown in Fig. 1 at TU Chemnitz facilities using screen printing. Silver particle based ink has been used for printing the conductive traces. PET (from Melinex [14]) with 100 µm of thickness was used as the substrate. In order to validate the concept, measurement has been done. Measurement was performed in an anechoic chamber. Two vertically polarized horn antennas (Rohde & Schwarz HF906) were placed at a distance of 45 cm from each other. The horn antennas have an average gain of 10 dBi in the frequency band from 1 GHz to 18 GHz. Fig. 4 shows the bi-static measurement set-up. For better isolation, an absorber is placed in between the horn antennas. The horn antennas were connected at the two ports of an Agilent Performance Network Analyzer (PNA E8364B). The power delivered by the PNA is 3 dBm. In order to increase the signal-to-noise ratio, an averaging of 64 samples was applied. The measurement was conducted between the operating frequencies 2 GHz to 5 GHz.

The chipless RFID tag under test is placed at a distance greater than R (far-field distance) from the horn antennas. The far-field distance for the horn antennas is found to be 34 cm @ 2 GHz. Several measurements were conducted for different distances from 35 cm to 1.5 m and 1 m was found to be the larger reading distance. A complex S_{21} can be measured using this configuration. A calibration technique

explained in [17] has been used here. In this calibration technique an empty chamber measurement is required, i.e., without any tag in order to remove all the static noise. Additionally, a reference measurement was also conducted to take into account of the effect of antennas. For this purpose, a metallic plate is used as the reference object.

In order to validate the concept, 4 different tags were characterized. Initially, the distance R was chosen as 35 cm and the complex S_{21} was measured using the setup described before. The RCS of the tag was calculated using the calibration techniques explained in [17]. Fig. 5 shows the comparison between simulated and measured RCS for four different tag combinations IDs '000', '100', '111' and '010'.

Further the reading distance was increased and measurements were done for 50 cm, 80 cm, 1 m and 1.5 m. Fig. 5 shows the measured RCS at different distances, R. It was found that from 1 m onwards the curves start to become noisy. However, a good agreement between simulation and measurement was obtained as shown in the same figure. Most of the errors observed on figures are due to errors introduced in the measurement process. It was observed that at 1.5 m the curves become too noisy making the tag undetectable. However, 1 m reading distance is the highest reported reading distance for a printed tag which proves the candidature of printed tags in low cost mass production applications.

V. CONCLUSION

A 3 bit chipless RFID tag able to be printed using mass production techniques is designed. Several prototypes of chipless RFID tags were fabricated on PET substrate using screen printing technique and measured in an anechoic chamber. The use of screen printing allows fast mass production of chipless tags in a very short time. A maximum reading distance of about 1 m was obtained with a transmission power of 3 dBm. The obtained results confirm the use of low cost printed tag for mass market applications.

REFERENCES

[1] IDTechEx (2009). Printed and Chipless RFID Forecasts, Technologies & Players 2009-2029.

[2] A. Panizza, RFID prospects for Europe:Item level tagging and Public Transportation. JRC Scientific and Technical Report, JRC European Commission, 2010.

[3] Gartner, "Market Trends: Radio Frequency Identification, Worldwide, 2007-2012". Gartner Dataquest, 2008.

[4] I. Jalaly. and I. Robertson, "RF barcodes using multiple frequency bands," IEEE MTT-S International Microwave Symposium Digest, 2005.

[5] I. Jalaly. and I. Robertson, "Capacitively-tuned split microstrip resonators for RFID barcodes," European Microwave Conference, 2005

[6] V. Deepu, A. Vena, E. Perret and S. Tedjini, "New RF Identification Technology for Secure Applications," IEEE International Conference on RFID-Technology and Applications (RFID-TA), Guangzhou, China, 2010.

[7] A. Vena, E. Perret, S. Tedjini, G. Tourtollet, A. Delattre, F. Garet and Y. Boutant, "Design of Chipless RFID Tags Printed on Paper by Flexography," IEEE Transaction on Antennas and Propagation, Issue 99, September 2013.

[8] H. Jang, W. Lim, K. Oh, S. Moon, and J. Yu, "Design of Low-Cost Chipless System Using Printable Chipless Tag With Electromagnetic Code," IEEE Microwave And Wireless Components Letters, Vol. 20, No. 11, November 2010.

[9] W. Lee, H. Jang, K. Oh, J. Yu, "Design of Chipless Tag with Electromagnetic Code for Paper-based Banknote Classification," Proceedings of the Asia-Pacific Microwave Conference 2011.

[10] B. Shao, Q. Chen, R. Liu, and L. Zheng, "Design Of Fully Printable And Configurable Chipless RFID Tag On Flexible Substrate," Microwave and Optical Technology Letters, Vol. 54, No. 1, January 2012.

[11] B. Shao, Y. Amin, Q. Chen, R. Liu, and L. Zheng, "Directly Printed Packaging-Paper-Based Chipless RFID Tag With Coplanar LC Resonator," IEEE Antennas and Wireless Propagation Letters, Vol. 12, 2013.

[12] B. Shao, Q. Chen, Y. Amin, R. Liu, L. Zheng, "Chipless RFID tags fabricated by fully printing of metallic inks," Springer Ann. Telecommun., Vol. 68, pp. 401–413, 2013.

[13] A. Vena, A. Babar, L. Sydänheimo, M. Tentzeris, and L. Ukkonen, "A Novel Near-Transparent ASK-Reconfigurable Inkjet-Printed Chipless RFID Tag," IEEE Antennas and Wireless Propagation Letters, Vol. 12, 2013.

[14] DuPont Teijin Films, Available : http://www.dupontteijinfilms.com/FilmEnterprise/Datasheet.asp?ID=117&Version=US

[15] E. Knott, J. Shaeffer, and M. Tuley, "Radar Cross Section," second edition, SciTech Publishing, 2004.

[16] R. Nair, E. Perret, and S. Tedjini: "A Novel Temporal Multi-Frequency Encoding Technique for Chipless RFID Based on C-sections", Progress in Electromagnetic Research (PIER) B, Vol. 49, pp.107-127, 2013.

[17] A. Vena, E. Perret, and S. Tedjini, "Chipless RFID tag using hybrid coding technique," IEEE Transactions on Microwave Theory and Techniques, Vol. 59, pp. 3356-3364, 2011.