TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

Erja Sipilä

Novel Manufacturing Methods and Materials for UHF RFID Tags in Identification and Sensing Applications

Julkaisu 1421 • Publication 1421

Tampere 2016

Tampereen teknillinen yliopisto. Julkaisu 1421
Tampere University of Technology. Publication 1421

Erja Sipilä

Novel Manufacturing Methods and Materials for UHF RFID Tags in Identification and Sensing Applications

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Tietotalo Building, Auditorium TB109, at Tampere University of Technology, on the 28th of October 2016, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2016

ISBN 978-952-15-3822-3 (printed)
ISBN 978-952-15-3839-1 (PDF)
ISSN 1459-2045

TO MY FAMILY

– Anna, Aaro and Mika –

ABSTRACT

The continuously increasing amount of radio frequency identification tags needed in our daily lives, not forgetting the broadly widening concept of the Internet of Things, sets high demands on the tag materials selection and manufacturing processes. The huge amount of needed tags requires environmentally sustainable material selection together with the requirement of very low cost. In addition, the manufacturing capacity needs to be very high, hence high-volume capable production methods are needed. In addition to identification applications, also sensing applications established with radio frequency identification tags are of great interest in many application fields.

This thesis reports the possibilities of radio frequency identification tags manufactured on eco-friendly substrate materials using conductive inks and photonic sintering. The used manufacturing methods use raw materials efficiently. Especially brush-painting together with photonic sintering is capable for low-cost high-volume manufacturing. In addition, the possibilities of radio frequency identification tags for humidity sensing applications are studied.

The results of this thesis confirmed that the materials and processes studied in this thesis are suitable for environmentally friendly low-cost radio frequency identification tag manufacturing. Especially brush-painting of regular screen printing conductive inks, both silver and copper oxide ink, on wood and cardboard substrates combined with photonic sintering confirmed to be a very good choice for the application area focused in this thesis. Furthermore, especially the use of screen printable copper oxide ink for identification applications is a very low-cost possibility. The results showed that humidity sensing with passive ultra-high frequency radio frequency identification tags, which were manufactured with regular screen printing silver ink on wood substrate without any coating on the tag, is a very promising approach.

ACKNOWLEDGEMENTS

This work was carried out at the Department of Electronics and Communications Engineering at Tampere University of Technology during the period 2014–2016.

I wish to thank my supervisor, Professor Leena Ukkonen, for her excellent guidance and strong support throughout my thesis work. I wish also to sincerely thank my instructor, PhD Johanna Virkki, for her ever-continuing support and believe in my thesis work. A special thank undoubtedly belongs to the Head of the Department, Professor Lauri Sydänheimo. Without his strong trigger for initializing this thesis work this thesis would have not been done. He had the perfect perception for the right time for this thesis. In addition, I am grateful to my co-authors Toni Björninen, Manos M. Tenzeris, Lianglun Chen, Yanan Ren, Jianhua Wang and Jun Liu.

During the thesis making period I was part of the Wireless Identification and Sensing Systems Research Group (WISE) lead by Professor Leena Ukkonen. At the same time I worked in my normal job as an electronics lecturer. Combining of these too very interesting and demanding work areas was not easy at all, there were times that I thought it was impossible, but Leena and Johanna guided me through those times towards the destination of my research work, and together we did pass all the difficulties in this journey.

This thesis was financially supported by the Ulla Tuominen Foundation, Jenny and Antti Wihuri Fund, and KAUTE Foundation, whose support I here greatly acknowledge.

I wish to thank my friends, Katja Laine and Kati Kokko, for their support and encouragement during this thesis process. I am greatly indebted to my parents, Orvokki and Timo, and my brother Tapio and sister Marja, for their love and support during all the years.

Most of all I own my heartfelt thanks to my husband Mika, and to our children Anna and Aaro, for their unconditional love and support during this process. Without the endless support and flexibility of my family the making of this thesis would have been impossible.

Tampere, August 2016,

Erja Sipilä

Supervisor	Professor Leena Ukkonen Department of Electronics and Communications Engineering Tampere University of Technology
Instructor	PhD Johanna Virkki Department of Electronics and Communications Engineering Tampere University of Technology
Pre-examiners	Associate Professor Ville Viikari Department of Radio Science and Engineering Aalto University School of Electrical Engineering
	Associate Professor Pedram Mousavi Department of Electrical and Computing Engineering University of Alberta, Faculty of Engineering
Opponent	Professor Heli Jantunen Microelectronics Research Unit Faculty of Information Technology and Electrical Engineering University of Oulu

Tampere University of Technology
Faculty of Computing and Electrical Engineering
Department of Electronics and Communications Engineering

TABLE OF CONTENTS

LIST OF PUBLICATIONS

This thesis consists of an extended summary and the following publications:

I Sipilä, E., Virkki, J., Wang, J., Sydänheimo, L. and Ukkonen, L., ”Brush-painting and Photonical Sintering of Copper Oxide and Silver Inks on Wood and Cardboard Substrates to Form Antennas for UHF RFID Tags”, International Journal of Antennas and Propagation, Vol. 2016, 2016. 8 p.

II Sipilä, E., Virkki, J., Sydänheimo, L. and Ukkonen, L., “Reliability of Passive UHF RFID Copper Tags on Plywood Substrate in High Humidity Conditions”, Proceedings of IMAPS Nordic Conference, Tørnsberg, Norway, June 5th–7th, 2016, 5 p.

III Sipilä, E., Liu, J., Wang, J., Virkki, J., Björninen, T., Cheng, L., Sydänheimo, L., and Ukkonen, L., “Additive Manufacturing of Antennas from Copper Oxide Nanoparticle Ink: Toward Low-Cost RFID Tags on Paper- and Textile-based Platforms”, Proceedings of the 10th European Conference on Antennas and Propagation (EuCAP), Davos, Switzerland, April 10th–15th, 2016, 4 p.

IV Sipilä, E., Virkki, J., Sydänheimo, L., and Ukkonen, L. “Experimental Study on Brush-Painted Passive RFID-Based Humidity Sensors Embedded into Plywood Structures”, International Journal of Antennas and Propagation, Vol. 2016, 2016. 8 p.

V Sipilä, E., Ren, Y., Virkki, J., Sydänheimo, L., Tenzeris, M.M., and Ukkonen, L. “Parametric Optimization of Inkjet Printing and Optical Sintering of Nanoparticle Inks”, Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal, April 13th–17th, 2015, 4 p.

VI Sipilä, E., Virkki, J., Sydänheimo, L., and Ukkonen, L. ”Experimental Study on Brush-Painted Metallic Nanoparticle UHF RFID Tags on Wood Substrates”, IEEE Antennas and Wireless Propagation Letters, Vol. 14, 2015, pp. 301–304.

VII Sipilä, E., Virkki, J., Sydänheimo, L., and Ukkonen, L. 2014. ”Effect of Sintering Method on the Read Range of Brush-painted Silver Nanoparticle UHF RFID Tags on Wood and Polyimide Substrates”, Proceedings of the IEEE RFID Technology and Applications Conference (RFID-TA), Tampere, Finland, September 8th–9th, 2014, pp. 219–222.

AUTHOR'S CONTRIBUTION

Publication I, "Brush-painting and Photonical Sintering of Copper Oxide and Silver Inks on Wood and Cardboard Substrates to Form Antennas for UHF RFID Tags", was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with Johanna Virkki. The measurements were done and the results were analyzed by the author. The author wrote the manuscript, and the co-authors commented and improved the text.

Publication II, "Reliability of Passive UHF RFID Copper Tags on Plywood Substrate in High Humidity Conditions", was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with help of Johanna Virkki. The tests and measurements were done by the author with help of Johanna Virkki, and the results were analyzed by the author. The author wrote the manuscript, and the co-authors commented and improved the text.

Publication III, "Additive Manufacturing of Antennas from Copper Oxide Nanoparticle Ink: Toward Low-Cost RFID Tags on Paper- and Textile-based Platforms", was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with Johanna Virkki and Toni Björninen. The measurements were done and the results were analyzed by the author with help of Johanna Virkki and Toni Björninen. The author wrote the manuscript, and the co-authors commented and improved the text.

Publication IV, "Experimental Study on Brush-Painted Passive RFID-Based Humidity Sensors Embedded into Plywood Structures", was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with help of Johanna Virkki. The tests and measurements were done by the author with help of Johanna Virkki. The results were analyzed by the author. The author wrote the manuscript, and the co-authors commented and improved the text.

Publication V, "Parametric Optimization of Inkjet Printing and Optical Sintering of Nanoparticle Inks", was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with Johanna Virkki and Yanan Ren. The measurements were done by the author with help of Yanan Ren. The results were analyzed by the author. The author wrote the manuscript, and the co-authors commented and improved the text.

Publication VI, "Experimental Study on Brush-Painted Metallic Nanoparticle UHF RFID Tags on Wood Substrates", was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with Johanna Virkki. The measurements were done and the results were analyzed by the author with help of Johanna Virkki. The author wrote the manuscript, and the co-authors commented and improved the text.

Publication VII, ”Effect of Sintering Method on the Read Range of Brush-painted Silver Nanoparticle UHF RFID Tags on Wood and Polyimide Substrates”, was contributed by the author together with the co-authors as follows: the tests were planned and the test samples manufactured by the author with Johanna Virkki. The measurements were done and the results were analyzed by the author with the help of Johanna Virkki. The author wrote the manuscript, and the co-authors commented and improved the text.

LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating Current
ACA	Anisotropic Conductive Adhesive
ACF	Anisotropic Conductive Film
ACP	Anisotropic Conductive Paste
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
DC	Direct Current
DSB	Double-Sideband
DSB-ASK	Double-Sideband Amplitude Shift Keying
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
EPC	Electronic Product Code
FM	Frequency Modulation
FSK	Frequency Shift Keying
HF	High Frequency
IC	Integrated Circuit
ICA	Isotropic Conductive Adhesive
ID	Identifier Code
IoT	Internet of Things
IPL	Intense Pulsed Light
IR	Infra-Red
LF	Low Frequency
NP	Nanoparticle
PAR	Polyarylate
PC	Polycarbonate

PDMS	Polydimethylsiloxane
PE	Polyethylene
PET	Polyethylene Terephthalate
PI	Polyimide
PM	Phase Shift Modulation
PSK	Phase Shift Keying
PTC	Power Transmission Coefficient
R/W	Read/Write
R2R	Roll-to-Roll
RF	Radio Frequency
RFID	Radio Frequency Identification
RH	Relative Humidity
ROM	Read-Only Memory
UHF	Ultra-High Frequency
UV	Ultra-Violet

1 INTRODUCTION

In this thesis novel materials and manufacturing methods for ultra-high frequency (UHF) radio frequency identification (RFID) and sensing applications were studied. The aim was especially towards environmentally friendly, low-cost, and high-volume manufacturable UHF RFID tags. This study was mainly experimental, most of all exploring the possibilities of very eco-friendly substrate materials: cardboard and wood, together with electrically conductive ink based additive manufacturing methods: inkjet printing, brush-painting and 3D direct write dispensing, combined with photonic sintering. Two kinds of conductive inks: nanoparticle (NP) inks and regular screen printable inks were used in this study, and with both ink types the use of both silver and copper-based inks was studied. The possibilities of these material and manufacturing methods were also studied for humidity sensing with passive RFID tags without any additional parts, such as on-board sensors.

The need for digital wireless communication in the world is rapidly increasing. The era of the Internet of Things (IoT) is beginning requiring new ultra-low-cost methods for communications between various objects. In addition, the requirements include reliability and durability in different environments [Vya09]. One possibility to enable the tremendous increase of the IoT is to use passive UHF RFID tags for identification and sensing purposes [Mar10, Vir12]. These tags enable rapid wireless identification of objects. In addition, the possibility to integrate sensing functionalities to RFID is a great benefit in this technology.

Until today the main issue slowing down the RFID technology becoming a mainstream technology in identification applications is the cost [Wan06]. Even though the prices for UHF RFID tags are not very high at the moment, beginning from few cents of euro upwards, this price level is yet too high for very low-cost products e. g. in retail trade. Bar-code technology is still strongly utilized in retail, even though it needs a line-of-sight in order to function. Hence, cost reduction is a major issue when considering and choosing RFID tag manufacturing methods and materials, and this way enabling the beginning of the era with the IoT and RFID. In addition, the high-volume production capability is essential, especially when thinking of the era with the IoT.

The necessity of cost minimization leads to minimization of material usage together with the utilization of fabrication processes with as few fabrication steps as possible [Dea10]. In addition, the expected massive increase of RFID tags leads also to massive increase of electronics waste at the end of a tag's lifecycle. This means that environmentally smart choices have to be done in materials selection as well as in manufacturing method selection. Renewable materials and minimal need of toxic or harmful materials and chemicals is extremely desirable in future electronics [Jun15]. These facts drive to exploit additive manufacturing methods in RFID antenna manufacturing [Dea10], which are suitable to environmentally friendly high-volume, preferably roll-to-roll (R2R), processing [Lee11a].

RFID technology can have also other uses than just identification of objects [Rid10]. It can act for instance as a sensor [Fen11, Rid10]. In this case the RFID tag is a multifunctional item, making possible identifying together with sensing and monitoring some variable [Rid09]. At the same time the cost of RFID tag should remain in the same level as without sensing functionalities. The sensing functions of a tag preferably should not add tag cost, because the extra cost may be unbearable from the end-user point of view [Kha14], and this way the era of the IoT could be postponed. For example, the RFID tag can act as a humidity sensor and at the same time provide identification of an object. The sensor functioning can be established with the same electrical tag design and tag parts as the identification, e. g. not necessarily requiring any special integrated circuit (IC) or antenna design. The humidity affects the tags functioning in a predictable way.

The study results in this thesis show that cardboard and wood-based substrate materials together with photonical sintering of conductive inks is a very interesting approach for the future green high-volume electronics manufacturing for identification and sensing applications. In this study the focus was to find materials and methods that are low-cost, environmentally friendly and capable for high-volume production. In this study it was found that the use of NP inks in the application types presented in this study does not give any significant benefits over regular screen printable inks. On the other hand, handling of NP inks is much more demanding than handling of screen printable inks, and the price of NP inks is higher than the price of screen printable inks. In addition, when thinking about the unknown health issues with NP inks, the use of screen printable inks is found to be a good choice. However, if very precise layout is needed, then NP inks together with inkjet printing is a good choice. The first tests of wood-based humidity sensor tags show that with screen printable silver ink the results are very promising, but with screen printable copper ink the results show that this approach is not a working solution for humidity sensing. At least this material combination needs lots of further research work, and probably the use of a conformal coating.

1.1 Objectives and scope of the thesis

The aim of the work was to find out how the chosen novel materials and manufacturing processes suit to low-cost high-volume eco-friendly RFID tag manufacturing for identification and sensing applications. Especially interesting was the suitability of wood-based substrate materials with very low-cost copper oxide screen printable ink to photonic sintering process. This work is mainly experimental, testing in practice the possibilities of this novel approach.

Due to the lag of fine pitch capability of the brush-painting process, which is widely used in this study for antenna manufacturing, the antenna design is chosen according to the manufacturing process, not according to the best RF performance of an antenna. This same situation is also with other antenna manufacturing processes, the manufacturing process sets always some limitations to the antenna design, and the antenna designer and manufacturer aim towards the best possible antenna performance under the dominant circumstances. Thus, the antenna design issues are not in the scope of this thesis.

1.2 Structure of the thesis

This thesis consists of an extended summary followed by seven publications. The extended summary is divided into 8 chapters providing relevant background on the topic and presenting the main results. Chapter 1 gives introduction to the need for the novel materials and manufacturing methods for RFID tags, and introduces briefly the aims, scope and results of the thesis. Chapter 2 introduces the basic principles of the RFID technology. In Chapter 3 different antenna manufacturing techniques are presented. Chapter 4 is about substrate materials for RFID tags, and Chapter 5 introduces the basics of electrically conductive inks. Chapter 6 concentrates on different sintering methods, and especially on photonic sintering. In Chapter 7 the utilization of RFID tags as sensor elements is introduced. Chapter 8 is the final conclusions and remarks of the thesis. In addition, in this chapter a summary of the results of publications is presented.

2 RFID TECHNOLOGY

RFID is a wireless identification technology, which is more and more exploited also in wireless sensing of different quantities. The very basic idea in an RFID system is simply to establish radio frequency (RF) communication between two parts: a reader and a transponder (tag).

The main idea in normal RFID identification system is to uniquely identify an object [Dob08]. The benefits of an RFID system include e. g. that it does not need a line-of-sight, as do for instance bar codes [Dob08, Fin03]. The identification of multiple items simultaneously is also very possible [Fen11]. RFID technology for identification is nowadays successfully used for instance in some libraries, where the loaning of books can be done transferring simultaneously a pile of books through an RFID reader. The challenges in RFID systems include e. g. that electromagnetic (EM) waves have difficulties in penetrating water and metals [Fen11, Fin03].

One great benefit of RFID tags is that they can be embedded into various products, because they do not have to be visible from outside. The item has to be permeable to RF waves, at least to some extent. The optical transparency is not an issue with RFID technology. On the surface of a product the RFID tag would be exposed to different environmental conditions, especially in open-air use. Rain, snow, air moisture and other weather conditions would affect it in a great extent. Fortunately, implementing a tag inside a structure can reduce environmental effects affecting it. However, environmental issues exist also inside various structures, but they are milder than on the outer surface.

The RFID system consists of three main parts: a tag, a reader and a server [Fen11]. The basic principle of an RFID system is presented in Fig. 1. The tag consists of a substrate with antenna manufactured on it and IC attached on the antenna [Fin03]. Nowadays RFID tags are often protected with a plastic layer on top of the tag. In many cases the protective layer is a sticker surface enabling easy attachment of a tag to various surfaces. Photos of factory made high frequency (HF) and UHF tags, and their rolls, are in Fig 2. The UHF tag in Fig. 2 has a copper antenna and the HF tag has an aluminium antenna. Every tag, or more precisely every IC, has its own identifier code [Fen11]. The object to be identified has an RFID tag, or the tag is a part of the object. The reader sends and receives information to and from the tag, and submits it to the server part [Fen11, Fin03]. The server is a computer, which is an interface between RF system and the application layer [Fen11].

In general, there are two basic phenomena with which an RFID tag can receive and transmit data and power: near-field and far-field operation. Basically HF RFID tags use near-field coupling and UHF RFID tags use far-field operation utilizing back-scattered EM waves [Lai15, Wan06]. In general, near-field systems have smaller read ranges than far-field systems [Sam08]. In addition, the data transfer rate is more limited in HF systems than in UHF systems due to the narrower bandwidth of HF systems compared to UHF systems [Cha07b, Sar02]. The UHF systems have benefits over the HF systems, such as the longer read range and generally smaller size, but the UHF systems are more susceptible to the dielectric and conducting objects near them [Dob05, Nik07]. Sensing capabilities are more feasible with UHF than with HF systems as a result of the benefits of UHF systems. In this study only UHF RFID tags are used [Publications I–VII].

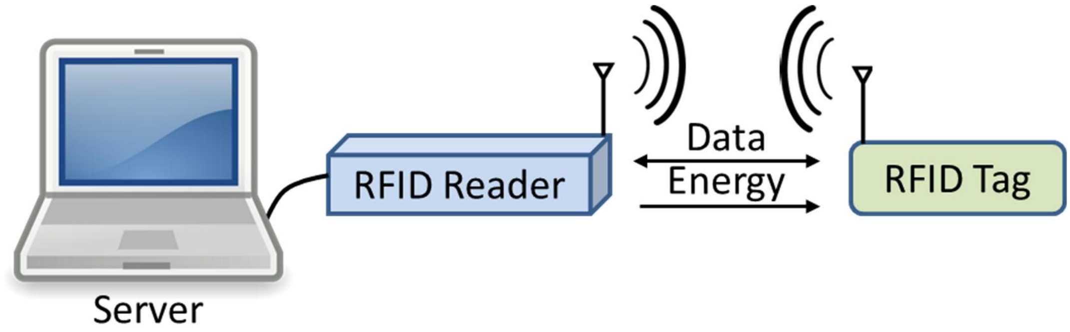


Figure 1 A basic principle of an RFID system.

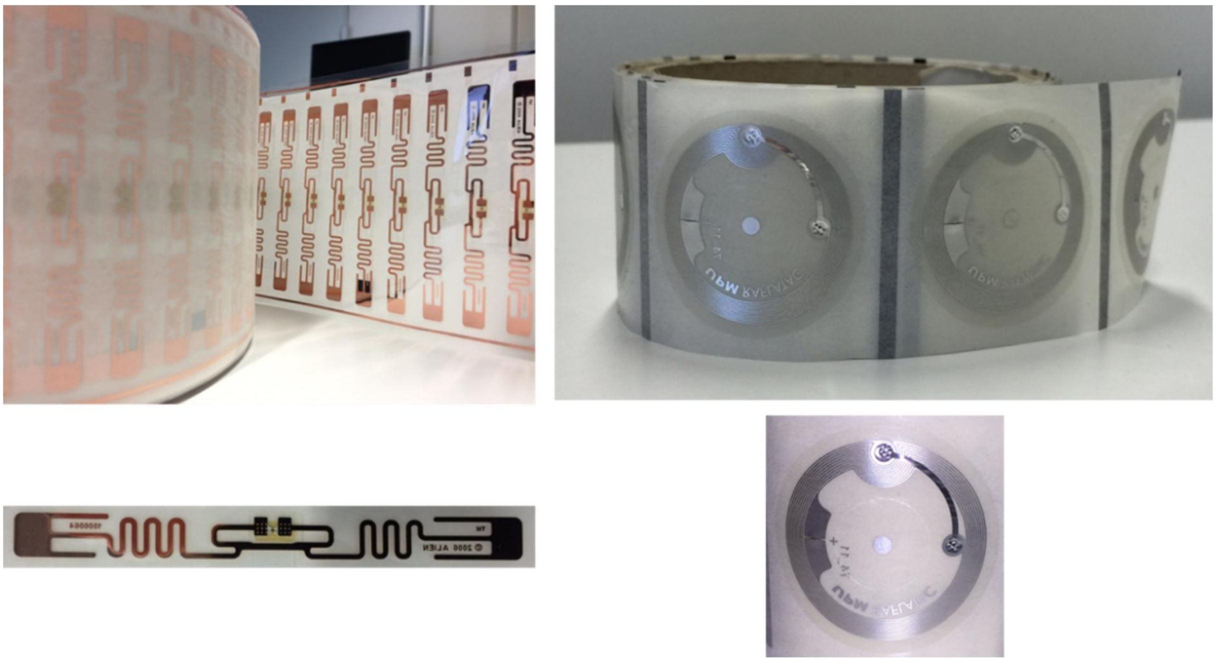


Figure 2 Photos of UHF and HF RFID tags.

Top left photo: A roll of copper UHF tags, Lower left photo: A single UHF tag.

Top right photo: A roll of aluminium HF tags, Lower left photo: A single HF tag.

2.1 Near-field coupling

The basis of near-field coupling between a reader and an RFID tag antenna is in Faraday's principle of magnetic induction [Cha07b, Wan06]. The principle of near-field communication is thoroughly described in [Wan06]. It is briefly introduced in the following paragraphs based on [Wan06].

In near-field coupling the reader passes a large alternating current (AC) through its coil. This results in an alternating magnetic field near the reader antenna. The RFID tag utilizing this coupling method has a smaller coil, and when it is in the magnetic field of the reader, AC will be induced to tag's coil. Fig. 2 right side photos show an example of HF tag, which utilizes near-field coupling. In these photos the antenna coil can clearly be seen. The near-field coupling technology uses load modulation in transmitting data from RFID tag. In load modulation the tag's coil current is proportional to the load applied to the tag's coil. If the tag IC applies a varying load to its own coil, a signal can be encoded as tiny variations in the magnetic field strength, which represents the tag's identification code (ID). The reader coil can detect the small increase in current, caused by the variation in the magnetic field, flowing through it.

Near-field coupling is a very straightforward way to realize RFID systems. However, it has some major drawbacks, e. g. the operating distance is limited, and when frequency of operation is increasing, the operation distance is decreasing. In addition, the available energy significantly decreases with an increasing distance. For the needs of today and future applications, the properties of near-field coupled RFID systems are insufficient in many cases. Hence, far-field operating systems are probably the choice for future in many application areas.

2.2 Far-field operation

The basic operation principle of a far-field utilizing RFID system is quite simple, it is based on coupling of EM waves [Fin03]. The data transmission technique used with far-field RFID tags is backscattering [Sam08, Sto48, Wan06]. It was first introduced in 1948 in [Sto48]. The basic principle of modulated backscattering is presented in Fig. 3 [Wan06]. The reader has a dipole antenna to transmit and receive EM waves [Wan06]. The electric and magnetic fields are perpendicular to each other and to the propagation direction of the propagating EM [Wen05]. Electromagnetic waves, when captured by a tag antenna, induce an alternating voltage across the antenna terminals. The IC rectifies the needed direct current (DC) supply voltage from the induced AC voltage [Cha07b, Fen11, Vir13a, Wan06]. The IC activation signal can carry also commands with which new information to the IC's memory can be written [Wan04]. The tag modulates the digital signal in order to transmit the information stored in the IC [Fen11]. The reader catches the transmitted wave from the tag and transforms the received information to a binary code [Fen11]. The binary data will be proceeded to the server [Fen11]. Left side of Fig. 2 shows an example of an UHF RFID tag. The dipole antenna dipole can clearly be seen in those photos. The main limitation in far-field operation is the amount of energy that is reaching the RFID tag from the reader [Wan06]. In this study far-field operation in UHF RFID tags is used [Publications I–VII].

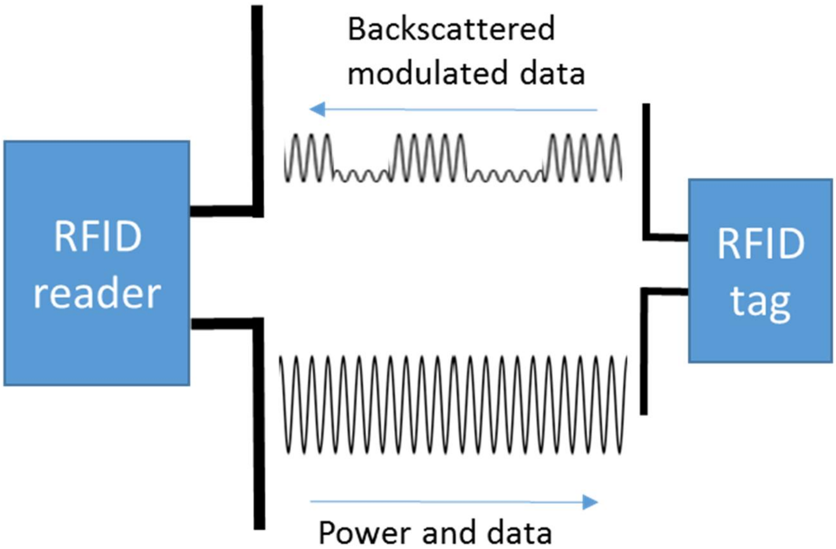


Figure 3 The basic principle of modulated backscattering.

Antenna can be tuned to the desired frequency by adjusting its size and shape, and it absorbs most of the energy that it receives on that frequency [Wan06]. In the case of impedance mismatch at this frequency, the tag antenna reflects back some of the energy from the EM wave, and the reader can detect this energy [Wan06]. The amount of energy that is backscattered from tag can be varied with varying tag antenna impedance [Fin03, Sam08, Wan06]. The antenna impedance can be changed by a transistor or a diode, which is placed between the two arms of a dipole antenna [Dob08, Ric10, Sam08], the transistor or diode is in the IC. When the transistor or diode is conducting, it short-circuits the arms of the dipole antenna, this way changing the antenna impedance [Sam08]. The antenna impedance is not significantly affected if the transistor is not conducting.

The information from tag to reader is most often transmitted using amplitude modulation (AM), frequency modulation (FM) or phase-shift modulation (PM) methods [Das10, Fin03, Haw10], or more precisely their digital counterparts, which are based on the AM, FM and PM: amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying (PSK) [Das10].

The basic idea behind AM is that the amplitude of the transmitted signal from tag to reader is changing according to the unique binary code of the IC [Fin03, Das10, Rid10]. The amplitude of the carrier wave and the amplitude of the data signal are combined and the resulting signal has changing amplitude according to the data stored in the IC. Usually, in binary data, lower amplitude level means logical 0, and higher level means logical 1. The frequency remains constant in AM. The main idea behind FM is to change the signal frequency according to the unique identification code of the IC, and the basic idea in PM is to change the phase of the signal according to the unique code of the IC [Das10, Zhe07]. In PM the frequency and amplitude of the signal are not affected [Zhe07].

The basic idea in AM is presented in Fig. 4 and the FM signal with same kind of carrier wave and modulating signal is presented in Fig. 5. The basic idea of PM is presented in Fig. 6.

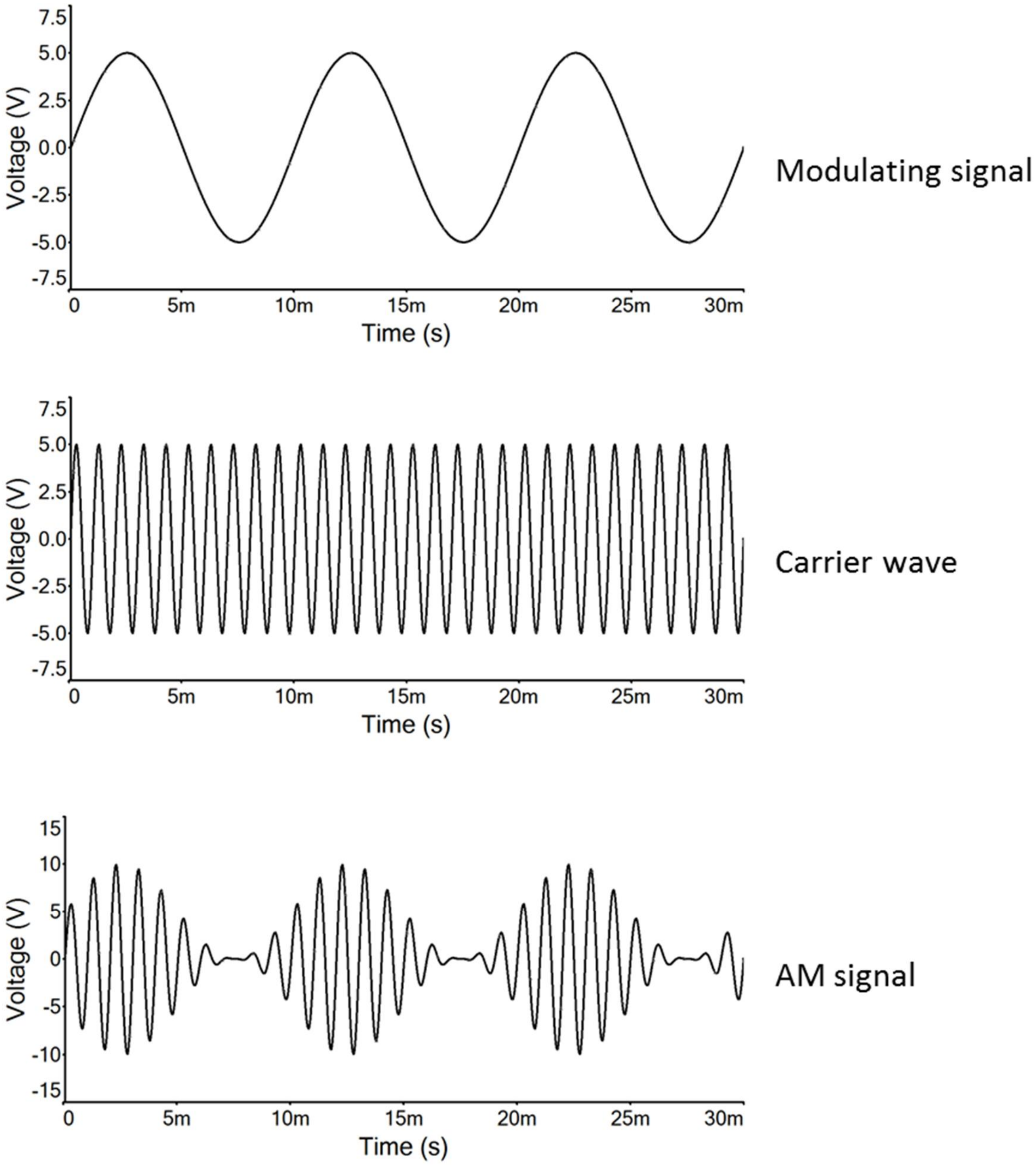


Figure 4 A basic idea of AM.

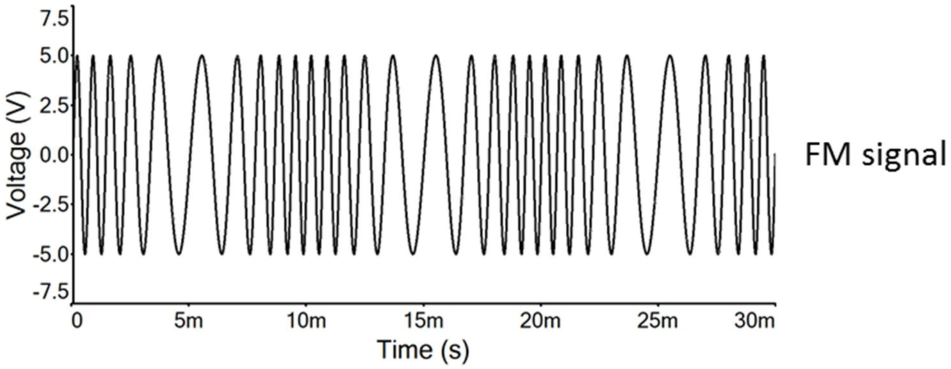


Figure 5 A basic idea of FM.

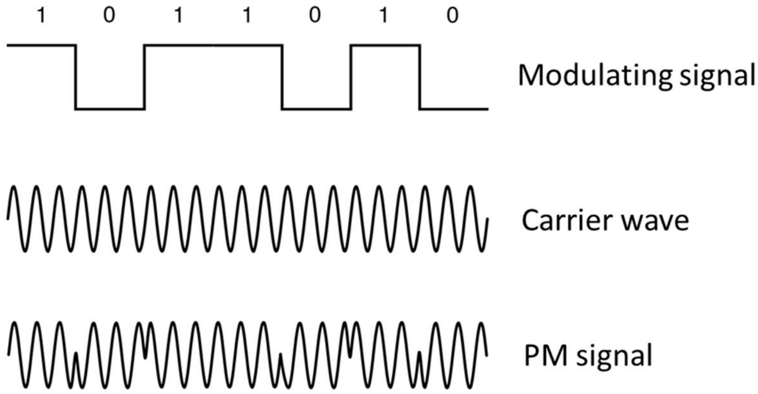


Figure 6 A basic idea of PM.

2.3 RFID system classification according to used frequency or power source

The RFID systems can be classified according to the frequency they use, and according to the power source they use [Fen11]. The RFID systems according to frequency can be divided basically to three classes: low frequency (LF), high frequency and ultra-high frequency tags. In addition, a microwave system frequency area can be discriminated in UHF band. The frequencies in each of these are presented in Table 1 with some basic advantages and drawbacks of each of them.

The active RFID tags have battery as an on-board energy source [Fen11]. However, the battery increases the size and cost of the tag [Wan06], and in addition, the maintenance of the tag, the battery replacement, is very difficult. The biggest benefit of active tags compared to passive tags is their significantly longer read range. The active tags can have read ranges of several hundreds of meters [Fen11]. In semi-passive systems the tag has a battery, but it is used only to power up the IC, but the transmission module works in a passive way, utilizing the modulated backscattering principle [Cha07b, Fen11]. The properties of the semi-passive tags are between passive and active tags.

Table 1 Frequency ranges of different RFID systems with their advantages and drawbacks for passive systems [Cha07b, Dob05, Fen11, Fin03, Rid09].

Frequency range	Range	Advantages	Drawbacks	Application examples
LF Often 125 kHz	Few cm up to appr. 2 m, typically < 0.5 m	Tolerant to metals and water No restrictions of frequency use	Low data transmission rate Affected by electrical noise	Animal tracking Identifying metal objects
HF Often 13.56 MHz	Typically appr. 1 m	Quite tolerant to metals, water and electrical noise Possibility to read multiple tags simultaneously Faster data transmission than in LF	Worldwide use of the 13.56 MHz frequency Limited range Water and metals tolerance not as good as with LF	Credit cards, Access control cards, Passports
UHF 860 MHz – 960 MHz In Europe 865.6 MHz - 867.6 MHz	Appr. few meters, typically 4 – 5 m	Long range High data transmission rate Possibility to read multiple tags simultaneously Low-cost manufacturing	Absorbed by water Reflected by metals Interference with other applications	Supply chain, IoT
Microwave Often 2.45 GHz	Typically appr. 1 m	Very high data transmission rate Possibility to read very many tags simultaneously Very small size	Greatly absorbed by water Greatly reflected by metals	Cold chain management, Environment monitoring, Electronic toll collection

In general, the antenna design together with the IC power consumption mainly determine the read range of a passive tag [Ore11]. Hence, when maximizing the read range of a tag these issues should be in major role during the design process. In additon, the antenna manufacturing process sets limitations to the antenna design, which has to be taken into consideration during tag design process.

Fortunately, very sufficient read ranges can be achieved also with antenna layouts optimized e. g. according to the manufacturing method. In this study, due to the brush-painting process, antenna layout is designed mainly to be suitable to the manufacturing process, and at the same time to achieve a sufficient read range for most UHF RFID application areas [Publications I–IV, VI, VII].

2.4 IC and IC attachment

The RFID tag needs an IC in order to function. The IC contains nowadays more information than just the simple ID code of the chip. The IC can have additional read-only memory (ROM) and/or read-write memory (R/W), which the reader can interact with. The ROM can contain for instance additional details connected to the item the tag is attached on. This information is typically something that don't need to be read every interrogation time of the tag, but this information is available when needed [Wan06]. The R/W memory can typically be used e. g. for storing time stamps or needed history data, for instance item's previous owners [Wan06].

The IC can be attached to the antenna via a strap, or, more often nowadays in high-volume production, by using anisotropic conductive adhesive (ACA) with flip chip technology. A factory made strap interconnection can be seen in the left photos of UHF tags in Fig. 2, and the factory made HF tag of right photos in Fig. 2 utilizes flip chip technology. The chip is under the aluminium antenna in Fig. 2 right photos, unfortunately it cannot be clearly seen. The reliability of the interconnection between the IC and the antenna is a very interesting research area, but it is not in the scope of this thesis.

In this study the used IC is NXP UCODE G2iL series IC [NXP14]. The chip has 128 bit electronic product code (EPC) memory, 64 bit tag identifier code (ID), and a low wake-up power of 15.8 μW (-18 dBm) [NXP14]. Tag ID includes a 32 bit factory locked unique serial number assigned by the IC manufacturer [NXP14]. The used IC utilizes double-sideband amplitude shift keying (DSB-ASK) modulation method [NXP14], which is an AM technique. In DSB-ASK modulation a finite number of amplitude levels are used [Bro15], usually for binary signals two amplitude levels are in use. Sideband includes all the frequencies in the modulated signal, except the carrier frequency. All modulation techniques produce sidebands. The upper sideband consists of signal components with higher frequency than the carrier frequency, and lower sideband consists of signal components with lower frequency than carrier frequency [Dob08]. The upper and lower sidebands both exist in AM signal, signal with both sidebands is called double-sideband (DSB) signal. The used IC, NXP UCODE G2iL, is very suitable to multiple application areas, such as fashion, retail, electronics, supply chain management, container and product identification [NXP14].

IC mounted on a strap is very feasible in research purposes because it is easy to attach in laboratory by hand [Dea10]. The usage of it allows studying tag performance without concerns about IC attachment. A strap with an IC can be glued on the antenna e. g. with isotropic conductive adhesive (ICA), or in other words, most often conductive epoxy. In this study two component Circuit Works

Conductive Epoxy CW2400 is used for joining the strap on an antenna pattern area. The CW2400 has silver particles in an epoxy resin. A basic structure of a strap is that the IC is attached to the antenna fixture, the strap, using ACA flip chip technology [Dea10]. A small conductive pattern is etched or otherwise manufactured on a polymer, usually on a polyimide (PI), film, and the IC is flip chip bonded on it [Dea10]. The strap used in this study is presented in the photos of Fig. 7. A basic principle of strap joining is presented in Fig. 8.

In the upper photo of Fig. 7 a bare strap is seen. The IC can be seen in the middle of the strap. When looking on the IC very closely one can see cured ACA in the edges of the chip. The strap substrate material is polyethylene terephthalate (PET) and the strap conductors are copper. In the lower photo of Fig. 7 a strap attached on a RFID tag antenna is seen. The IC is again in the middle of the strap, but now it is facing down, towards the tag substrate. The strap is attached on the RFID substrate using conductive paste, the paste can be seen in the photo when it is squeezed out from the strap edges.

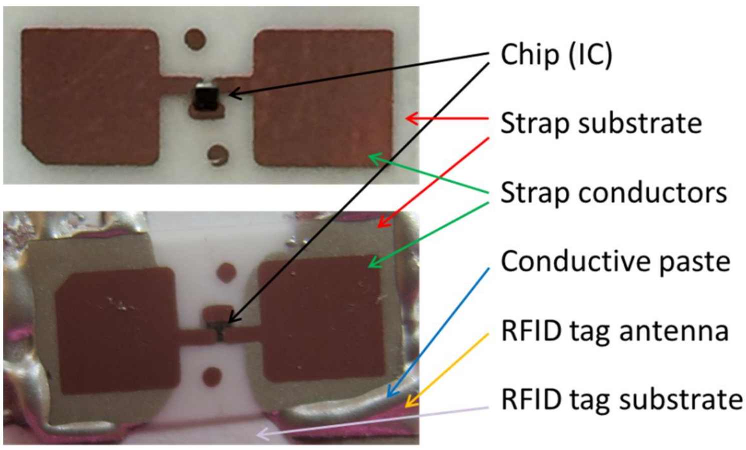


Figure 7 A photo of the strap used in this study (upper photo), and a photo of a strap attached on a substrate (lower photo).

ACA is a polymer based material with electrically conductive particles in it. It is available in two formats: anisotropic conductive paste (ACP) and anisotropic conductive film (ACF) [Liu01, Opd12]. Both can be used with RFID tags, but ACP is more common in RFID industry, mainly because of its simpler application process. ACP can be dispensed to the right place in the antenna pattern area [Opd12], meanwhile ACF has first to be cut off from a tape, and after this it has to be aligned to the right place on the substrate, preferably following with a prebonding stage [Cha02, Udd03]. Altogether, the ACP process has fewer process steps than the ACF process [Liu07, Udd03]. The basic principle of ACA flip chip joining is presented in Fig. 8. The conductive particles in ACA can be e. g. copper, silver, gold, nickel, or very often metal coated polymer spheres. The concentration of conductive particles is lower than the percolation threshold, the conductive particles do not touch each other in the ACA, and establish conductive paths, before the ACA is cured in the bonding process [Liu01, Udd03]. The conduction through ACA is established by applying pressure and heat simultaneously to the ACA. The ACA is cured by heat under pressure, and this way both electrical and mechanical joint is maintained in the interconnection even after removal of the bonding pressure [Cha02, Liu07].

Flip chip technology with ACA is a very fast and cost-effective process in R2R high-volume production. However, it has some drawbacks when used together with very temperature sensitive or rough substrate materials [Asc97]. The ACA process needs generally quite high process temperatures, usually in the scale of 160°C to 190°C. For instance low-cost polymers, like polyethylene (PE) or PET, cannot withstand the temperature requirements, nor can paper-based substrate materials. In addition, the ACA process uses high pressure to establish the conduction from IC to antenna. The conductive bumps on IC and the pads on substrate have to get in mechanical touch with conductive particles of the ACA, and the ACA has to be cured under pressure so that the mechanical interconnection is established and maintained [Cha02, Liu07, Udd03]. The bumps and pads are small, in the scale of tens of micrometres [Dea10], so if the substrate used in this process is uneven, like for instance wood substrate, the use of flip chip technology with ACA is very hard, almost impossible [Asc97].

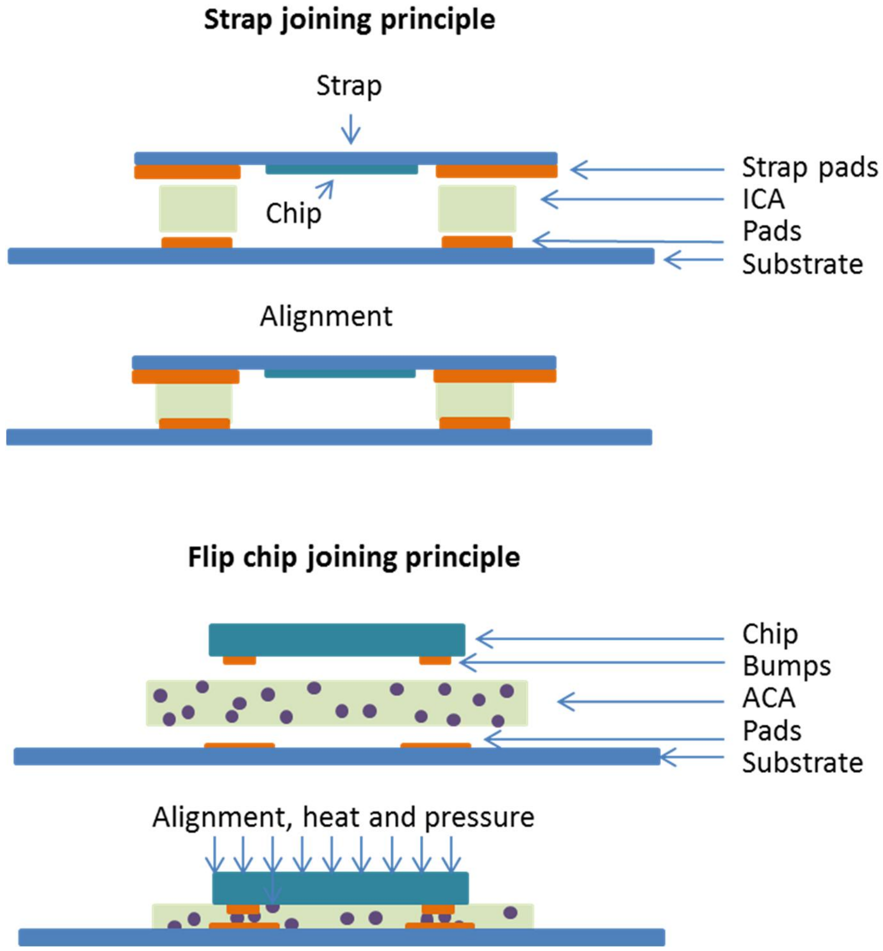


Figure 8 Basic principles of strap and flip chip joining.

When comparing strap and flip chip processes it can be seen that the strap manufacturing requires flip chip attachment as well. In the case of a strap, the IC attachment is done in another manufacturing line, most often in a totally different factory, and then the ready-made straps are sold to RFID tag manufacturers. The RFID manufacturers attach the straps to their tags. In ACA flip chip process the RFID manufacturer does IC attachment at the same time in the same place. This saves cost and reduces total process steps. However, in this case the IC attachment machinery requirements are more demanding, the alignment of a flip chip has to be done very precisely, and at the same time heat and pressure has to be applied to the joint.

In this study strap joining technology is used [Publications I–VII]. This technology was chosen because of the rough surfaces of the substrates, especially wood and textile substrates [Publications I–IV, VI, VII]. In addition, even though cardboard seems to have quite even surface when looking in macroscopic scale, in microscopic scale the surface is not totally even. Hence, also the surface of cardboard might be too rough for flip chip joining. In addition to surface roughness, also the substrate surface softness is demanding for flip chip technology. When applying the required pressure during IC attachment process, the pads and conductive particles easily sink into the soft substrate, and the mechanical and electrical interconnections are not established. Even though the ACA flip chip joining is the smartest choice in many cases, it is not suitable to all material combinations. Hence, the choice of the IC attachment technology has to be considered with every product individually.

2.5 RFID measurements

There are different parameters that can be measured from an RFID system. The operation of a tag can be measured in normal use conditions, or e. g. in a specially made RFID measurement chamber, anechoic chamber, where environmental issues do not affect the results [Dob08]. The benefit of the use of RFID measurement chamber is that the measurement environment is known every time the measurements are done [Kue13]. This way the results are comparable to each other, even though they would have been done in separate days. However, the RFID tag testing in normal use condition is important, because normal environment differs significantly from the conditions in an anechoic chamber. In normal use environment multiple objects and surfaces are absorbing and reflecting the signals. When using normal use environment as a test environment the environmental issues affecting tag performance can be evaluated, and the right tag choice for every application and client can be made.

For example read range, antenna radiation pattern, antenna directivity and tag's sensitivity can be measured [Bal05, Der07, Dob08]. Antenna radiation pattern describes how a directive antenna concentrates its radiated power propagating in a specific direction [Dob08]. However, a dipole antenna, which is used in UHF RFID tags, is not very directive [Dob08]. The directive gain in definite direction of an antenna is the ratio of the radiation intensity in any direction to the intensity averaged over all directions [Dob08]. The directivity of an antenna is the directive gain in the direction with maximal quantity [Dob08]. In this thesis read range is the predominant variable which has been measured [Publications I – VII]. Thus the following paragraph is concentrating on describing measuring of read range.

2.5.1 Measuring read range

One very important parameter, but by no means not the only, that describes the performance of an RFID tag is the read range. The read range is the maximum distance at which the data stored in the IC can successfully be read by the reader. This means that the tag has to receive enough power for IC activation and the signal it backscatters back to the reader has to be strong enough [Dob08, Fin03]. When the distance between the tag and the reader is too long for successful data receiving, either the tag IC does not receive enough power, or the transmitted signal from the tag to receiver is smaller than the reader's sensitivity. The maximal distance between the tag and the reader antenna in an environment without reflections or external disturbances is the theoretical read range of a tag [Publication I, III, V, VI, VII][Vir13a].

Power transfer between antenna and IC is best described by a power transmission coefficient (PTC) τ [Rao05, Vir13a]. This describes the power which is delivered to the load and reflected back to the reader [Vir13a]. Realized gain can also be used when describing tag antenna operation [Vir13a]. Realized gain is the PTC multiplied by the antenna gain [Vir13a].

Threshold power is an important parameter of an RFID system; it is the minimum power needed to activate the tag IC [Bjö09]. Threshold power of an arbitrary tag can be expressed as

$$P_{TS} = \frac{P_{IC}}{G_{tx}G_{tag}\tau\left(\frac{\lambda}{4\pi d}\right)^2\left|\hat{p_{tx}}\cdot\hat{p_{tag}}\right|^2}, \tag{1}$$

where P_{IC} is the sensitivity of the RFID IC, G_{tx} and G_{tag} are the gains of the reader and tag antenna, τ is the PTC, λ is the wavelength of the signal from the reader, d is the distance between the tag and the reader antenna, p_{tx} and p_{tag} are the unit electric field vectors of the transmitting antenna and tag antenna. The inner product of the electric field vectors describes the power loss due to possibly mismatched polarization planes between the reader and tag antenna [Publications I, III, V, VI][Vir13a].

The sensitivity of an RFID tag indicates the minimum field strength that is required for the tag to detect the reader signal, process data and to send the response signal [Der07]. Theoretical read range, presented in equation (3), can be obtained from tag's sensitivity using the Friis' equation, which is presented in equation (2) [Bal05, Der07, Rao05]

$$P_{tag} = P_{tx}G_{tx}G_{tag}\left(\frac{\lambda}{4\pi d}\right)^2, \tag{2}$$

where P_{tag} is the power received by the tag antenna, P_{tx} is the power transmitted by the reader antenna. When finding out theoretical read range of a tag, the P_{tag}

is assumed to be in the minimum value, in the threshold value P_{TS}. The theoretical read range can now be calculated with the following equation (3)

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{tx}G_{tx}G_{tag}\tau}{P_{TS}}}. \quad (3)$$

Usually tag sensitivity measurement is done in an anechoic chamber [Rud11]. The tag sensitivity is very much affected by the object to which the tag is attached [Der07].

The Tagformance measurement system, which is used in this study [Publications I–VII], calculates the theoretical read range of a tag using its measured threshold power along with the measured forward losses [Publications I, III–V, VII][Vir13a]. The forward loss describes the link loss between the generator's output port to the input port of an equivalent isotropic antenna placed at the tag's location [Publication I, III–V, VII][Vir13a]. The measurement of threshold power P_{TS} in Tagformance measurement system is done so that the transmitted power is increased until the tag responds to the query command of the reader [Bjö09]. The main things affecting the P_{TS} are the τ, and the sensitivity of the IC [Bjö09]. In this study the sensitivity of the used IC is -18 dBm [NXP14, Publications I, III, IV, VI]. The forward loss from the transmit port to the tag is calculated using a reference tag during the calibration procedure of Tagformance [Publication V][Bjö09, Vir13a]. The reference tag is provided by the measurement system manufacturer [Bjö09]. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels and can be calculated as:

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}}, \quad (4)$$

where λ is the wavelength transmitted from the reader, effective isotropic radiated power (EIRP) is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, P_{TS} and L_{fwd} are the measured threshold power and forward losses correspondingly [Publications I, III, V–VII][Vir13a]. Equation (4) is derived from equation (3) with the knowledge that [Dob08, Fin03]

$$EIRP = P_{tx}G_{tx}. \quad (5)$$

When using Tagformance as the measurement device, it should be noted that there are no other tags in close proximity. In real life, especially with the increase of the IoT, multiple tags can be very close to each other. This causes changes in the tag's operation, because each tag antenna acts as a shielding and reflecting object [Vir13a]. In addition, when operating in normal living environment, there are changing environmental conditions, such as temperature and humidity, together with varying distance between the reader and the tag. All these factors affect the tag's operation. However, the theoretical read range measurement gives the benefit of doing measurements in the same conditions, and this way the comparison of tags can be done reliably. Thus, the theoretical read range measurement is used in this study [Publications I–VII].

3 ANTENNA MANUFACTURING TECHNIQUES

In principle there are two ways of manufacturing antennas in RFID technology, the basic categories are subtractive manufacturing and additive manufacturing. The whole substrate is covered with conducting material in subtractive manufacturing, and then with some process, usually etching, the conductive material is removed from the areas where it is not needed. In additive manufacturing conductive material is added only to the places on a substrate where it is needed, hence the conductive material wastage is minimal compared to etching [Kim12, Hal11] or other subtractive manufacturing methods. Basic principles of subtractive and additive antenna manufacturing processes are presented in Fig. 9. The number of basic process steps in both manufacturing categories can be seen in Fig. 9. There are significantly more process steps with subtractive manufacturing than with additive manufacturing.

The use of additive manufacturing technologies in RFID antennas has been a widely researched topic recently [Kim15, Män09, Ram15, San15]. Etching has been widely used in the high-volume productions of RFID antennas [Dea10, Kim12], and it is the most used RFID antenna manufacturing method at present [Kim09b, Bjö09]. However, etching has many disadvantages, including waste of antenna material, e.g. copper, silver or aluminium, and the need of environmentally harmful chemicals [Dea10, Kim09b, Kim12, Mer10]. This can also be seen in Fig. 9 with subtractive manufacturing method. The trend to green electronics encourages developing and using other manufacturing technologies instead of etching. In addition, significant cost savings are expected with high-volume additive manufacturing of RFID tags [Kim11, Kim15, Ram15].

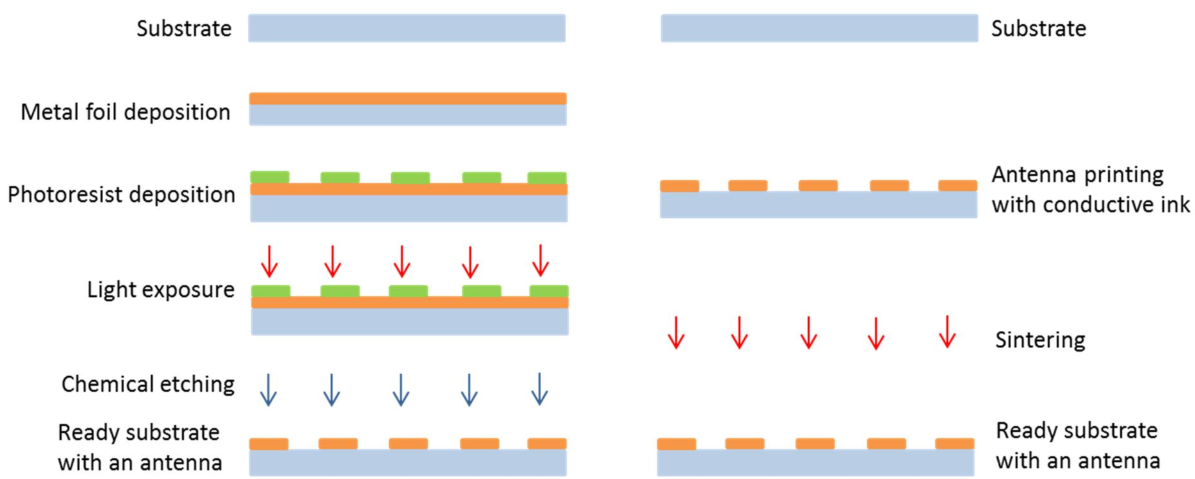


Figure 9 Basic principles of subtractive (chemical etching, left side of the picture) and additive manufacturing methods (printing, right side of the picture).

Various manufacturing technologies can be utilized in additive manufacturing of antennas [Kim12]. The additive manufacturing methods can be divided to two categories: direct-write techniques and techniques requiring a mask of some kind [Tek08]. The direct-write technologies offer the smallest wastage of conductive ink material, which leads to highest material cost savings [Tek08]. The direct-write techniques include e.g. inkjet printing and 3D direct write printing, while brush-painting and screen printing are included in the techniques requiring a mask. Each of these technologies has its own requirements for the ink material, and this is why every material–manufacturing method combination needs careful studying [Kim12].

The achieved thickness of the conductive layer affects also to the choice of the most appropriate manufacturing method. The penetration depth, or skin depth, of the conductive material sets the boundary condition for the manufacturing method [Bjö09, Wen05]. The current density is highest in the surface of a good conductor [Wen05]. The skin depth is the distance where the amplitude of the electric field has decayed to e^{-1} (0.37) of the amplitude at the conductor surface [Wen05]. Hence, the minimum requirement for the layer thickness of the conductive material can be considered to be the skin depth of the material. If the conductive layer of an antenna is too thin, thinner than the skin depth of the material, the current flow gets constricted and ohmic losses increase [Bjö09]. The equation for the penetration depth is

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}, \tag{6}$$

where f is the frequency, μ is the permeability (appr. μ_0), and σ is the conductivity of the material. In the case of bulk copper at 866 MHz frequency, with bulk copper resistivity of 16.78 nΩ·m [Ran91] and the permeability of a vacuum 1.2566371 μH/m, the penetration depth is

$$\delta = \frac{1}{\sqrt{\pi \cdot 866\ \mathrm{MHz} \cdot 1.2566371\ \mu\mathrm{H/m} \cdot \frac{1}{16.78\ \mathrm{n\Omega m}}}} = 2.22\ \mu\mathrm{m}, \tag{7}$$

and in the case of bulk silver in 866 MHz, with bulk silver resistivity of 15.86 nΩ·m [Ran91], the penetration depth is

$$\delta = \frac{1}{\sqrt{\pi \cdot 866\ \mathrm{MHz} \cdot 1.2566371\ \mu\mathrm{H/m} \cdot \frac{1}{15.86\ \mathrm{n\Omega m}}}} = 2.15\ \mu\mathrm{m}. \tag{8}$$

These results are for bulk copper and silver. The layer established with conductive inks, as well NP [Pol16] as non-NP conductive inks, have poorer conductivities than the bulk materials. Hence the penetration depth of layers made with all kinds of conductive inks is greater than the penetration depth of the same bulk material. From the penetration depth results with bulk materials it can be seen, that e. g. one layer of inkjet printed NP ink is not enough from this point of view. For example it has been found that the maximum conductive layer thickness of inkjet printed copper-based NP ink after photonic sintering is about 1 to 2 μm [Kan14, Pol16]. However, e. g. screen printed layers of conductive ink are thick enough from this point of view. For example average layer thickness with screen printable silver ink is found to be 21.5 μm [Bjö09].

In addition to the limit that penetration depth sets to the conductive layer thickness, and this way to the proper manufacturing method, the substrate surface is a major concern regarding conductive layer thickness [Publications IV, VI, VII][Vir12]. If the substrate is uneven, for instance because of the grains in wood or yarns in textile, a very thin layer is not feasible [Sag14]. Furthermore, paper-based, wood, textile or other ink absorbing substrates absorb the ink solution [Den11, Sag14, Vir14b]. This also sets demands to the ink layer thickness [Sag14] and ink viscosity [Tob11].

3.1 Etching

Antenna manufacturing by etching is widely used in high-volume production of RFID tags. The process is well-known [Mer10]. However, it consists of many process steps, which makes it time-consuming and expensive [Mer10]. In addition, the antenna material choices, which are used with etching technology, are limited, because the solvent is corrosive [Par06, Mer10]. Nowadays copper and aluminium are the most used antenna materials [Kim09b]. Due to an increasing ecological awareness, the environmental issues come more and more important, and in this scope etching is not a good choice.

The basic principle of etching is presented in Fig. 9. There is clearly seen that a major part of conductive material, metal foil, is removed and it is waste together with the etching chemicals. In addition, in Fig. 9 it can be seen that etching has more process steps compared to additive manufacturing methods, e. g. brush-painting or inkjet printing. If the production machinery is well automatized the multiple process steps do not necessarily slow down the production speed and the throughput of the process. However, many times multiple process steps slow down the process, and at least the needed production equipment is more complicated and probably more expensive. From this point of view the amount of process steps should be minimized.

3.2 Inkjet printing

Inkjet printing of NP inks is widely researched method for manufacturing RFID during recent years. It is an additive manufacturing method. The greatest advantage of inkjet printing is its ability to obtain very precise, thin and narrow structures [Fal12]. Inkjet printing is a direct write method, the designed pattern is transferred directly onto a substrate without any mask [Ami12, Lee11b, Ore11]. Inkjet printing is a drop-on-demand method [Ami12]: the ink flow is not continuous, and the ink droplets are ejected when needed. Inkjet printing has also drawbacks, e.g. the printing process is slow [Vir13a], when thinking of low-cost high-volume manufacturing, and the health issues of NP inks are not yet known thoroughly. Inkjet printing is suitable to many low-cost substrate materials such as papers [Ore11] and PET. In principle inkjet printing is suitable to R2R manufacturing [Kan14], but the slowness of the printing process, leading to low process throughput, makes it unsuitable for low-cost high-volume R2R manufacturing.

Small droplets are ejected from the print head towards the substrate in inkjet printing [Vir13a]. The printer adjustments, or printing parameters in other words, of inkjet printing are especially important [Vir13a]. The right printer adjustments depend on the interaction between used materials and print heads [Vir13a]. Basically the printer adjustments include: movement of print heads, movement of print stage, ejection of droplets, and fluid pressures [Vir13a]. The drop form and drop velocity are controlled with print head parameters [Vir13a]. The printing waveform affects to the drop form. The drop speed is an important printer adjustment [Lim13]. If the drop rate is too low, it can happen, that the ink volume delivered on the substrate is too small, leading to insufficient ink layer thickness or incomplete coverage of the pattern [Lim13]. These things affect the electrical properties of the printed pattern [Lim13]. In addition, too slow dropping velocity often leads to misdirection of droplets when they fall on the substrate [Lim13]. The drop speed can be adjusted with jetting voltage of an inkjet printer [Fuj10, Lim13]. Drying of the ink solvent during printing process can be controlled with substrate temperature [Kan11, Shi13]. The inkjet equipment used in this study is Fujifilm Dimatix DMP-2831, which is presented in Fig. 10 [Publication V]. The printing parameters of Fujifilm Dimatix DMP-2831 inkjet printer are presented in Table 2. By adjusting the cartridge temperature one can change the viscosity of the ink and this way reach the desired jetting performance [Fuj10]. The substrate is held in place in this machine by vacuum.

Inkjet printing needs low viscosity liquid phase ink materials [Par07, Vir13a]. The inkjet inks should fulfil at least the following properties: have a very low viscosity, where no component separation occurs during high acceleration, and electrically conductive structures are possible to make with them [Fal11]. In the case of inks in inkjet printing, the electrical conductivity is achieved via conductive particles in a liquid, and to achieve the minimal component separation the particles should be as small as possible [Fal11]. The inks are printed through nozzles on a substrate, and after ink drying a conductive line is established. Printed particles do not form uniform, conductive material. Therefore directly after printing the conductive line is not conducting [Fal11]. The inkjet printed pattern comes conductive via sintering; the conductive metal particles are sintered with each other establishing an electrically conductive connection between conductive particles [Par07].

One drawback with inkjet printing of RFID tags is that one printing layer produces very thin conductive layer. Especially with copper inks the conductivity is not good enough with one thin layer [Kim09b]. In addition, the very thin layer does not withstand e. g. the chip attachment process very well. Hence, multiple inkjet printed layers are needed for a good result [Ami12, Vya09]. In addition, with multiple inkjet printed layers also multiple sintering rounds are needed [Vya09]. This slows the process significantly.

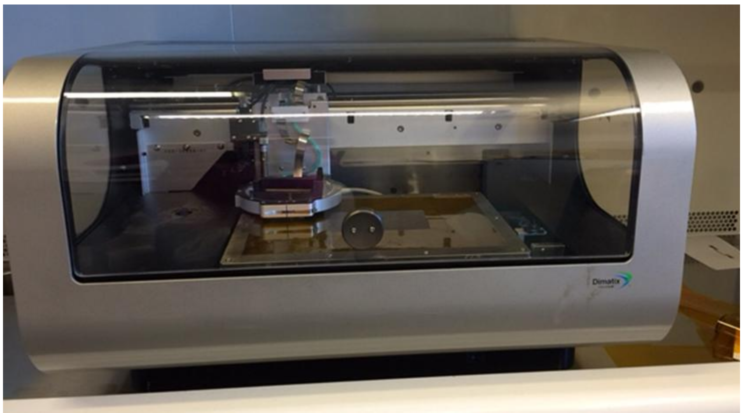


Figure 10 Fujifilm Dimatix DMP-2831 inkjet printer which is used in this study.

Table 2 Parameters for Fujifilm Dimatix DMP-2831 inkjet printer [Fuj, Fuj10, Vir13a].

Parameter	Allowable range
Jetting voltage	0 – 40 V
Cartridge temperature	28 – 70 °C
Drop spacing	5 µm – 254 µm
Printing resolution	100 dpi – 5080 dpi
Layer count	1 – max. depends on the ink
Substrate dimensions	210 mm x 315 mm with substrate thickness < 0.5 mm, 210 mm – 260 mm with substrate thickness 0.5 mm – 25 mm
Substrate thickness	0 – 25 mm
Substrate temperature	28 – 60 °C
Jets in use	1 – 16
Cartridge print height	0.25 mm – 1.50 mm

3.3 Brush-painting

Brush-painting combines parts of dispensing and screen printing. The conductive ink is applied directly to the brush in brush-painting. In laboratory manufacturing, e. g. in prototyping and testing, the ink can be applied to the brush by dipping the brush to conductive ink. However, in high-volume production the ink could be conducted directly inside the brush, and the amount of ink could be precisely measured out as in dispensing. This minimizes the ink wastage saving environment and money. Brush-painting needs a stencil like screen printing, because the ink application with a brush is not capable to form precise patterns. However, the ink is applied with the brush only to the area of stencil opening, only very little on the edges of the stencil, to minimize the ink consumption. In general, one brush-painted layer is enough for good conductivity, this reduces process steps compared to e. g. inkjet printing.

Brush-painting suits very well to R2R high-volume production, it is very fast. The basic idea of a high-volume R2R production line with brush-painting and photonic sintering is presented in Fig. 11.

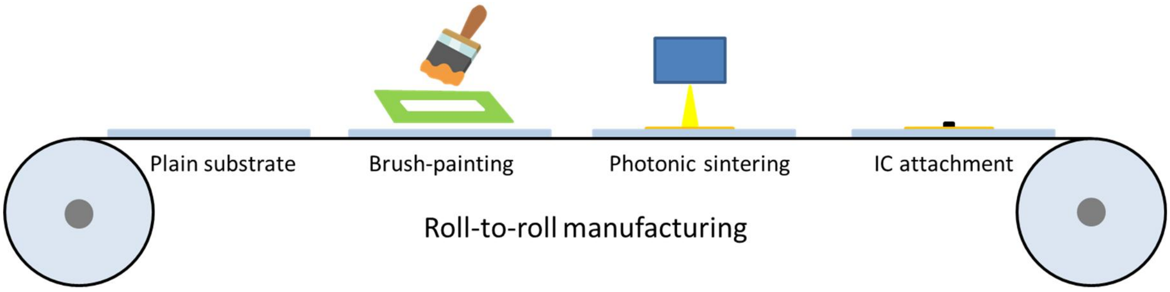


Figure 11 Basic idea in R2R RFID manufacturing with brush-painting and photonic sintering.

3.4 3D direct write dispensing

Direct write dispensing is an additive manufacturing process. One benefit compared to e. g. screen printing or brush-painting is that direct write dispensing does not need a stencil [Bjö15a]. 3D direct write dispensing requires a continuous material flow between the nozzle tip and the substrate, in comparison to e.g. inkjet printing, which does not need a continuous material flow [Bjö15a]. Electrically conductive inks are used in the 3D direct write dispensing used in this study [Publication III]. The pattern established with 3D direct write printer is conductive after sintering process. In comparison, many 3D printers use dielectric materials in printing process [Gia16, Vae13]. The result shape is not conducting. If, for instance, an antenna is manufactured with this kind of method, the result shape has to be coated somehow with electrically conductive coating [Gia16, She15]. Possibilities for coating include methods like electroplating and painting. The coating process is generally too slow for high-volume manufacturing, and it is an additional demanding process step. Hence, the dielectric material 3D printing process is not suitable for low-cost high-volume RFID tag manufacturing.

nScrypt tabletop series 3Dn direct write dispensing system is used in this study [Publication III]. Two precision dispensing pumps are computer controlled in this system [Bjö15a, Bjö15b]. The system is able to print on 3D surfaces with high precision [nSc]. The pattern to be printed can be imported from normal computer aided design softwares, such as Cadence [nSc12]. In this system regular screen printing conductive inks can be used [Bjö15b]. A photo of nScrypt tabletop series 3Dn direct write dispensing system is in Fig. 12. It is used in [Publication III]. There are multiple parameters, which can be adjusted via software in nScrypt

Tabletop 3Dn system [nSc12]. These parameters include e. g. speed, dispense gap, pressure, valve opening and closing [nSc12]. The most important properties of nScrypt tabletop series 3Dn direct write dispensing system are in Table 3.

Table 3 Properties of nScrypt tabletop series 3Dn direct write dispensing system [nSc].

Property	nScrypt tabletop series adjustment
X/Y accuracy	± 5 µm
X/Y maximum speed	300 mm/s
X/Y travel range	150 mm x 300 mm
X/Y resolution	0.5 µm
Z accuracy	± 5 µm
Z maximum speed	50 mm/s
Z travel range	100 mm
Z resolution	0.5 µm

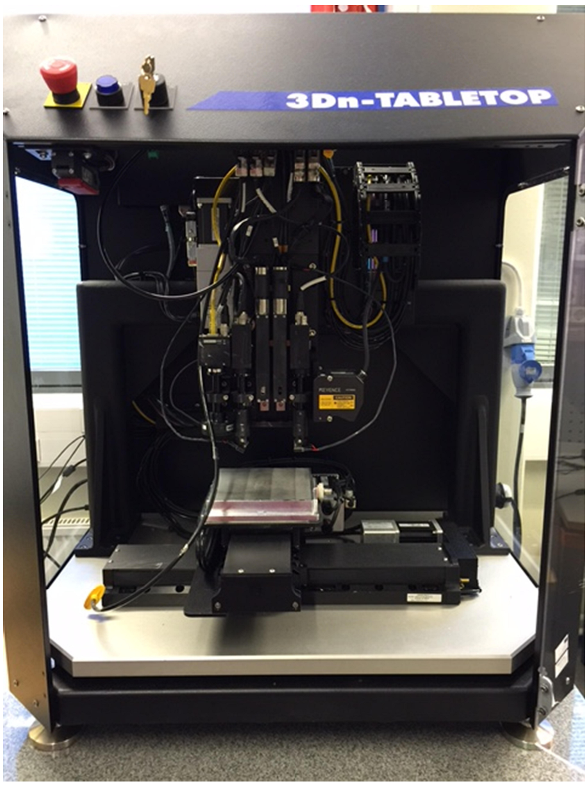


Figure 12 nScrypt tabletop series 3Dn direct write dispensing system, which is used in this study.

3.5 Other additive antenna manufacturing methods

There are also other choices for antenna manufacturing techniques in RFID manufacturing than etching and those additive manufacturing processes used in this study: inkjet printing, brush-painting and 3D direct write dispensing. All the technologies have their own benefits and drawbacks. In the following paragraphs some of them are briefly introduced.

Screen printing is much used in electronics manufacturing [Kha13, Kha15, Sug14]. Brush-painting is quite similar to screen printing, but the method for ink application is different in these techniques. The conductive ink is applied through a stencil, or a mask, on a substrate in screen printing [Bla05]. The stencil is on a fine fabric mesh [Bla05]. The stencil is flexible, so that when the squeegee is pressing it, it gets in touch with the substrate surface, and ink is applied on the surface [Kha13, Sug14]. The ink is applied on the stencil for instance by pouring [Bla05], or with some kind of dispensing method. One benefit of screen printing electronics is that quite thick layers of ink can be applied with one printing round [Sug14]. In addition, the pressure applied to the substrate is not very high, much lower than with gravure printing [Sug14]. The low pressure is beneficial with soft substrate surfaces. Normally the thickness of screen printed ink layer is in the range of tens of micrometres, but also as high as 100 μm can be achieved [Sug14]. There are two options for screen printing: flatbed and rotary screen printing [Kha15]. With rotary screen printing very high-volume production can be achieved, but the resolution of rotary screen printing is limited [Sug14]. The basic principle of screen printing is presented in Fig. 13.

Gravure printing is an intaglio printing process [Bla05, Kha15]. An engraved cylinder transfers the liquid phase ink on the substrate [Bla05]. The cylinder steeps in the conductive ink reservoir in the printing process [Bla05]. The excess ink is wiped away with a doctor blade [Bla05]. The remaining ink on the cylinder is transferred to the substrate under pressure against the cylinder [Bla05]. The image with gravure printing is established from separate cells [Bla05]. This can sometimes be a restriction for the use of this technology because there is always some jagging seen [Bla05]. In addition, the quite high pressure in this technology limits its application on flexible and otherwise soft substrate materials [Bla05]. However, with gravure printing a high-volume production can be established [Par15]. A schematic picture of gravure printing principle is presented in Fig. 13.

Flexography is a direct printing process [Bla05]. A pattern to be printed is formed on a rubber or polymer plate by photolithography [Kha15]. The result is a raised pattern that is attached to a cylinder [Kha15]. The conductive ink is applied to the cylinder with raised pattern quite similarly as in gravure printing. A cylinder is dipping in a reservoir of conductive ink, and then the ink is transferred to the cylinder with the print pattern [Kha15]. The pattern to be printed is then transferred on the substrate, only the inked areas are in touch with the substrate surface [Kha15]. A wide variety of different substrate materials can be printed using flexography, e. g. paper, cardboard, polymers, metals, and glass [Bla05]. Flexography is a very fast printing method, and it has been used widely in flat panel display printing [Sug14]. It is beneficial in resolution of the pattern [Kha15]. The printing pressure is low in flexography, which makes it suitable to flexible, and often quite soft, substrates [Sug14].

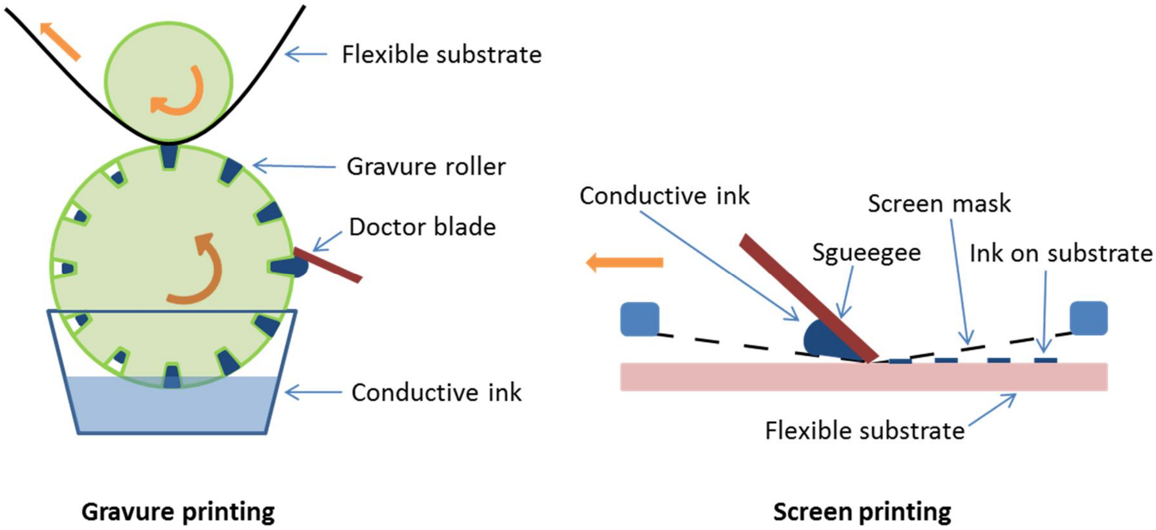


Figure 13 Principles of gravure printing and screen printing [Par15, Sug14].

4 SUBSTRATE MATERIALS

In order to ensure cost-effective electronics, the substrate material should be very inexpensive and it should be easily available in large quantities [Per12]. In addition, the substrate material should be eco-friendly, and it should not harm the environment during and after its life cycle. It would be even better, if a separate substrate is not needed at all, but the RFID tag could be manufactured directly on a surface of an object, or the tag could be embedded inside the object structure [Mer10]. The aim to eliminate the need of a separate substrate drives to investigate tag manufacturing on materials commonly used in e.g. logistics chains, retail and construction industry. Wood and cardboard are examples of these kinds of substrate materials, they are used in this study in [Publications I–IV, VI, VII].

In general, substrate affects the electrical performance of a tag with its electrical properties, such as loss tangent and relative permittivity [Kel12, Vir12, Vir13b]. The relative permittivity of a material describes how much energy is stored by the material when it is under influence of an external electric field [Vir12]. Loss tangent is a standard measure of lossiness of a dielectric [Wen05]. It describes the ratio of the conduction current magnitude to the displacement current magnitude [Wen05]. Loss tangent describes the quality of a dielectric, a good dielectric will have a very low loss tangent [Wen05]. Loss tangent has an effect on radiation efficiency of the antenna, and the tag's operating frequency is affected by the relative permittivity of the substrate [Kel12]. However, in this study the electrical properties of the used substrates are good enough for the application area in this thesis, they are not the main concern. The electrical properties of the RFID tags are quite much affected by the antenna design, which had to be optimised according to the new manufacturing methods in this study, not to the maximum electrical performance of the tags [Publications I–IV, VI, VII].

Furthermore, the evenness of substrate surface and porosity of substrate material affect much to the electrical characteristics of a RFID tag [Vir12]. The conductive ink can be absorbed into a porous material, and this way the thickness of the ink layer is not uniform throughout the substrate [Vir12, Vir13b]. Examples of ink absorbing substrate materials used in this study include cardboard, textile and wood [Publications I–IV, VI, VII].

4.1 Polyimide and other polymer substrate materials

Low-cost polymer substrate materials include e. g. polyesters, PE, polycarbonate (PC) and PET [Fal11, Nii14, Per12]. These materials have quite poor temperature tolerance, which makes their use in heat sintering difficult [Par15, Per12]. Especially PET is nowadays widely used in RFID manufacturing with traditional etching process [Bjö09]. PE has too poor properties, in addition to heat sintering, also to ACA flip chip attachment, hence it is not widely used in RFID high-volume production. However, many RFID manufacturers are studying the possibilities of PE as a substrate material, mainly because of its very low price.

PI is an example of a polymer substrate material that has good enough heat tolerance to heat sintering [Par15, Per09]. However, PI is significantly more expensive than for instance PET, and hence it is not suitable for low-cost R2R manufacturing [Per12]. PI is widely used in more demanding applications, where the temperature tolerance in so important that the higher price of PI is not a significant issue in purchasing RFID tags. In some applications also the colour of the material is a problem with PI [Kha15]. The colour of PI is very often brownish, as seen in Fig. 14, and if aesthetic values are important, this can be an unsuitable colour. There are also polymer materials with properties and cost somewhere between PE and PI, e. g. polyethylene naphthalate (PEN) [Jok02, Kha15], but most often even these possibilities do not offer enough low cost.

In high-volume low-cost eco-friendly production of RFID tags it is extremely important to be able to use substrate materials which cannot tolerate high temperatures. Many low-cost polymer substrate materials suffer from remarkable shrinkage in higher temperatures [All08], and of course these as well as e.g. paper or wood-based materials can burn in high temperatures.

Almost all the polymer materials are not environmentally friendly. One can find an exception in biodegradable polymers, but their properties are not suitable as electronics substrate materials, at least not yet. However, in future the biodegradable polymers as substrate materials are an interesting study topic. As a conclusion, when aiming towards low-cost green electronics, polymers are not the choice as a substrate material nowadays.

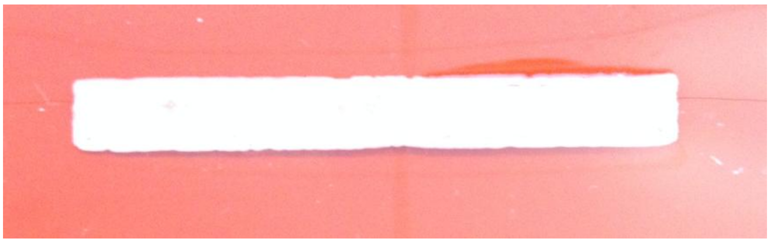


Figure 14 An inkjet printed silver line on PI substrate.

4.2 Cardboard and paper

Paper is a very promising and interesting substrate material for ultra-low-cost R2R manufacturing [Ami12, Kim13, Rid09]. The benefits of paper as a substrate material include: low-cost, very good availability, it is well suited to R2R processing, it has quite even surface, and it is biodegradable [Ami12, Kim15, Ore11, Rid09]. Paper takes only some months in landfill to decompose [Vya09]. On the other hand, organic substrate materials, such as paper-based materials, tend to be lossier because of their easy water absorption [Ami12].

There are numerous different paper types available [Rid09]. These vary in density, thickness, coating, texture, and dielectric properties [Rid09]. This wide variety of properties makes the RF characterization of paper very important [Rid09]. Paper, and paper-based substrate materials, e. g. cardboard, do not withstand the traditional etching process, hence other antenna manufacturing methods are needed with them. However, with proper additives, paper can be made quite hydrophobic [Ore11], in this way widening its possible application areas. In addition, with proper coating the surface of a paper can be made very even [Vya09].

In general cardboard has same properties as paper. Cardboard can be coated in different ways to form different kinds of surfaces. In addition, cardboard is delivered in very many different thicknesses. Due to the thicker structure of cardboard compared to paper, the conductive ink application processes together with sintering processes are easier to do with cardboard. However, again due to the higher thickness of cardboard compared to paper, it is more difficult to apply R2R manufacturing methods on cardboard. On the other hand, thin cardboards can easily be used with R2R, but thick cardboards are not suitable to R2R.

4.3 Wood

Wood is an interesting choice as a substrate material for RFID tags. It is biodegradable, aesthetically pleasing and much used material in many RFID application areas, e. g. logistics, construction and retail. However, it is lossy material, mainly because of its good moisture absorption capability. When thinking of low-cost high-volume manufacturing of RFID tags, the usual manufacturing method is R2R. However, wood is not suitable to R2R manufacturing, it is not flexible enough, not even in very thin versions. If the wood substrate is very thin, the wood becomes a bit flexible, but at the same time wood cracks easily. Hence, other manufacturing methods than R2R have to be used with wood substrates.

4.3.1 Plywood

Plywood is made with thin sheets of wood veneer [Vir13a]. These veneer sheets are glued together so that the adjacent plies have crossing grain directions [Vir13a]. The veneer layer structure and especially the adhesive layer between the veneer layers benefits the substrate against water uptake [Li15]. Plywood is used in many everyday items, e. g. floors, walls, containers, and furniture [Vir13a].

Plywood is prone to water uptake, and because of moisture absorbed in the plywood, its mechanical properties will worsen [Li15]. Thus, the moisture behaviour of plywood in the ambient conditions is essential to know [Li15]. The moisture distribution inside plywood is not always homogeneous, the outer layers in plywood absorb and desorb moisture faster than the inner layers [Li15]. When considering RFID tags on plywood substrates, they can be placed in very versatile places, ranging from outside conditions with varying temperature and air moisture, to inside conditions with quite stable atmosphere. This makes the reliability study of plywood-based RFID tags important.

The plywood surface is a difficult surface for RFID antenna manufacturing [Vir13a]. Especially true this is with inkjet printing [Vir13a]. The plywood has grains, which makes the surface of a plywood rough. It has valleys and hills, and when considering inkjet printing of NP inks, this surface roughness is huge [Vir12, Vir13a]. However, inkjet printed antennas on plywood have been reported to be functioning, when they are printed along the grain [Vir12, Vir13a]. The spreading of the ink is another problem with plywood in antenna manufacturing [Vir12, Vir13a]. The ink easily spreads along the grain in plywood [Vir12, Vir13a]. This is seen also in the microscope image in Fig. 15. In this image you can see silver ink on a plywood substrate. The grain of the wood is in vertical direction in the image. It can be seen in Fig. 15 that the silver NP ink has spread along the grains in the wood, but not even nearly as much in the perpendicular direction. This leads to conclusion that the antenna designs used with plywood should not have narrow gaps in grain direction [Vir13a]. The antenna designs on wood should have a one axis design rule: The most of the surface area of an antenna should be located on one axis [Vir12]. Furthermore, the dominating axis should be printed along the grain of wood [Vir12].

A photo of the plywood used in this study [Publications I, II, IV, VI, VII] is presented in Fig. 16. It is three-layer plywood; the thickness of it is appr. 3.8 mm.

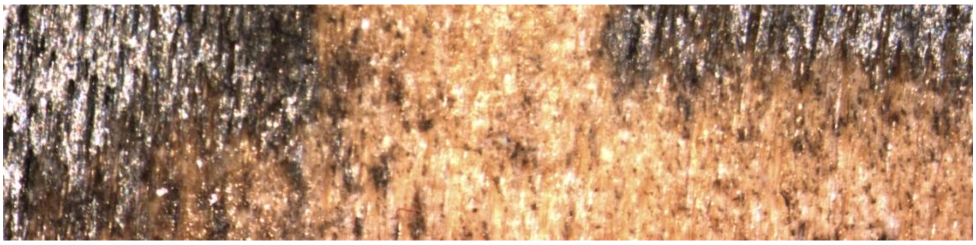


Figure 15 A microscope image of silver NP ink on plywood substrate. The grains on the plywood are in the vertical direction in the image.

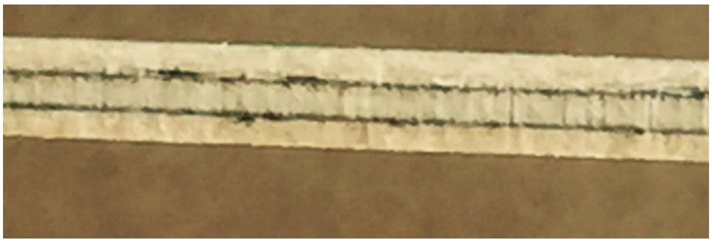


Figure 16 Plywood used in this study.

4.4 Other substrate materials

The ever widening use of RFID tags, especially with the dramatic spreading of the IoT, requires that the tags can be manufactured on very various substrates, enabling the embedding of RFID tags, and in general electronics, into structures.

One area with increasing interest is human identification and sensing applications. In this case the substrate material is very often some kind of textile material. This is a big application area of future UHF RFID tags [Vir14a]. The welfare and healthcare applications are rapidly increasing [Vir14a]. A major driving factor behind the increase of this application area is the increasing amount of elderly people. In addition, also other application areas, such as interior and furniture industries, use textiles. Textile substrate is used in this study in

[Publication III]. The surface of a textile material is uneven; the situation is quite the same as with wood substrate. Photonic sintering has been found to be suitable with both screen printable and NP conductive inks on textile substrates [Publication III][Vir14a].

Ceramics and ceramic composites is another material group that can be utilized in RFID tag substrates. Ceramic composites have, for instance, polymer and ceramic mixed together, e. g. barium titanate ($BaTiO_3$) and polydimethylsiloxane (PDMS) [Bab12]. The composite material can be made flexible compared to pure ceramic substrate material [Bab12]. The application areas of ceramic and ceramic composites substrates include e. g. identification of metallic objects. This is due to the generally high permittivity of ceramic materials [Bjö12], which condenses electric fields in the substrate and thus makes the antenna less sensitive to metal objects in its vicinity. In general, metal objects are difficult with RFID tags because usually the RFID tag is in parallel with the object surface [Bjö12]. This greatly changes the antenna impedance and radiation pattern, and lowers the antenna radiation efficiency [Bjö12]. However, ceramics are not low-cost nor especially environmentally friendly substrate materials, and they are not suitable to R2R manufacturing. Hence they are not a choice as a substrate material for the application area of this study.

5 CONDUCTIVE INKS

Inkjet printing together with NP inks has been recently widely researched. The most used inks are based on noble materials because of their chemical inertness in normal room conditions and good electrical conductivity [Fal11]. The most studied NP ink materials have been silver and gold, because of their good conductivity, and because the oxide formation during manufacturing process is not a problem with them [Kan11, Par07, Rid09, Tek08]. However, silver and gold are too expensive ink materials when considering low-cost high-volume electronics manufacturing [Dha13, Han11, Kan11, Kim09a, Lim13]. Hence, other conductive materials, e.g. copper, have to be considered [Dha13, Ryu11]. In addition to a lower-cost material choice, also other choices have to be made in order to reach the cost level that is required in RFID industry. This is important especially when considering the IoT and the massive increase in the RFID tag consumption. One possibility to decrease cost of RFID tags is to use conventional screen printing inks instead of more expensive NP inks.

Usually the electrically conductive inks used with RFID manufacturing are in a solution phase. Solution phase inks are typically made with metallic particles in an organic solvent [Dha13]. Nowadays silver flakes are the most used conductive material in direct printing [Dha13]. Silver inks in general consist of small silver particles, flakes or spheres, in a solution [Dea10]. The silver inks can be e. g. screen printed or gravure printed [Dea10]. The regular screen printable ink's silver particles are bigger than in NP inks.

In order to establish a conductive trace or antenna on a substrate, the metal particles have to be in metallic contact with each other [Per12]. Conductive inks have to be sintered after the application on the substrate in order to establish an electrical connection [Dea10, Lee11b, Rid09, Zen14].

Silver inks are predominant especially because of the silver's stability in normal room conditions [Dha13], in addition silver has the lowest resistivity of all metals [Per09]. Copper is a promising choice as ink material for low-cost high-volume production [Zen14]. Copper and silver have quite similar electrical conductivities, the conductivity of copper is only slightly poorer than the conductivity of silver [Dha13, Zen14]. Both NP copper ink as well as screen printing copper ink offer significantly lower cost than silver and gold counterparts [Kim12]. Copper has one major disadvantage compared to e.g. silver. Copper oxidizes easily in normal room atmosphere, and the copper oxide is an electrical insulator [Lee14, Par07]. If heat sintering is used with copper particles, it has to be done in vacuum or hydrogen atmosphere [Lee14]. The vacuum or hydrogen atmosphere is required to prevent the oxide formation and to render the already formed copper oxide to pure copper [Lee14]. The sintering of copper particles in ambient atmosphere has to be very quick so that oxidation has no time to proceed [Zen14]. In addition, copper has higher melting temperature than silver, and this also makes heat sintering of copper particles more demanding than that of its silver counterparts [Kan11].

There are basically three options for the type of conductive particle in copper-based inks. The metal particles in the conductive ink can be copper oxide particles (CuO), in which the CuO will convert to copper during the sintering process [Lim13]. The copper particles can also be coated with protective layer, which will evaporate during the sintering process [Lim13]. The third basic type of conductive particle is pure copper particles.

5.1 Nanoparticle inks

The conductive particles in NP inks have the diameter in nanometer scale. A melting point of a material is significantly lower on a surface of a particle than in a bulk material because of the weak bonding of the surface atoms [Dha13, Kan11, Lee11b]. In NPs the surface area is very big compared to the particle volume [Saj15], and thus the melting point of NPs can be remarkably lower than that of the same bulk material [Dha13, Lee11b]. In addition, the high surface-to-volume ratio makes NPs more reactive [Saj15].

The benefit of copper NP inks compared to silver or gold NP inks is that copper NP inks cost less [Ryu11, Par14a]. However, many commercially available copper NP inks have oxide on the surfaces of NPs [Ryu11], and the copper oxide is not conducting. This oxide formation sets requirements to the sintering process. Many different methods have been tried and studied in order to avoid the oxide formation in ambient condition, e. g. laser ablation and polyol process [Ryu11]. However, the additional process steps add the cost of the tag manufacturing, and increase the total material usage [Ryu11]. In addition, these oxide prevention processes can be environmentally harmful [Ryu11]. So, when considering low-cost high-volume green RFID tag manufacturing, these kinds of additional treatments are not a choice.

Copper NPs can be also manufactured of a pure copper [Ryu11], and this way there is not an oxide layer on the NP surfaces in the ink solution. However, pure copper NPs are much more expensive, hence they are not suitable for low-cost manufacturing [Ryu11]. Another drawback of pure copper NPs is that they are easily oxidized after storage in ambient conditions [Ryu11].

Harima NPS-JL silver NP ink [Publications V - VII] and ANI Cu-IJ70 copper NP ink [Publications V, VI] were used in this study. The properties of these used NP inks are in Table 4.

Many issues are still unsolved regarding the use of NPs. Recently there has been much discussion about the harmful effect of NPs to humans and environment [Saj15]. Many researchers think that the health and environment hazards of nanomaterial-based products have to be carefully studied before their wider use in different applications [Saj15]. The current knowledge of these issues is unfortunately seriously incomplete [Saj15]. The very small size of NPs, which leads to very high surface-to-volume ratio, makes the NPs more toxic [Saj15]. In addition, their penetration ability to human or animal tissue, or into plant, increases [Saj15]. The size of NPs is so small that even well-known materials behave in an unknown way in this size scale [Saj15]. It has been found that NPs with diameter less than 35 nm can penetrate the blood-brain barrier, NPs smaller than 40 nm can enter the nuclei of cells, and NPs smaller than 100 nm can enter into cells [Saj15]. When thinking about these dimension, the silver NP ink used in this study fall in all these size categories, and the copper NP ink partly falls to the category, where the NPs can enter cells. Silver NPs have found to be toxic to living cells [Gli14]. Copper oxide NPs have found to be cytotoxic to respiratory system [Aha15], and they have shown 10 to 20 times more toxicity than bulk copper with protozoa [Mor10]. Particle size is an important factor affecting the toxicity of NPs [Saj15]. However, also other NP properties affect the toxic effects of NPs, such as shape and material of NPs [Saj15]. As a conclusion from the health issues of NPs it can be said that they are harmful or even toxic to environment and living humans and animals, and this area needs intense further studying.

Table 4 Properties of the used NP inks in this study [Ani15, Har].

	Harima NPS-JL	ANI Cu-IJ70
Particle size (nm)	7	10-200, average 150
Resistivity (μΩ•cm)	6	5-7
Metal content (weight-%)	55	10-40
Viscosity (mPa•s)	11	10-20

5.2 Screen printing inks

Screen printing inks have larger conductive particles than NP inks. This makes them unsuitable to inkjet printing, because they would not come out of the nozzles of a print head [Vol11]. However, screen printing inks are very suitable e.g. to brush-painting, 3D direct write dispensing and screen printing, or in general, to processes where the ink is not dispensed through small nozzles. When considering low-cost high-volume R2R manufacturing the screen printable inks are a good choice, they are significantly cheaper than NP inks.

The larger conductive particle size leads also to a higher melting temperature compared to the melting temperature of NP inks [Vol11]. This can cause problems during sintering process, and this is why the sintering method must be carefully chosen for structures utilizing screen printing inks.

The screen printable inks used in this study are Novacentrix Metalon HPS-021LV Silver ink [Publications I, IV] and Novacentrix Metalon ICI-021 Copper Oxide Ink [Publications I–III]. The properties of the used inks are in Table 5. These both conductive inks are designed for screen printing [Nov, Nov11], thus they are very suitable also to brush-painting.

Table 5 Properties of the used screen printable inks in this study [Nov11, Nov].

	Novacentrix Metalon HPS-021LV	Novacentrix Metalon ICI-021
General description	Water-based Ag flake ink	Water-based copper oxide ink
Viscosity (mPa•s)	26 000	Appr. 300 000
Metal content (weight- %)	75	57.5
Particle size (µm)	2 and 4	Average 0.25

5.3 Other conductive ink materials

In addition to widely used silver, gold and copper particles in conductive inks also other materials for conductive particles are used. One promising low-cost particle material is nickel [Par14a]. Nickel oxidises easily [Kar01, Yam96], as do copper particles too [Par14a]. Sintering of nickel particles by heat in normal room atmosphere is almost impossible because the melting temperature of nickel (300°C - 600°C) is higher than the oxidation temperature (135 °C) of nickel [Par14a]. Thus, nickel particles need some other sintering method. The possibilities of nickel particles as the conductive media in conductive inks for low-cost high-volume RFID production are a very interesting research area for future.

One other possibility for the conductive material in conductive inks, which is now under intense research work, is graphene. Graphene is a carbon based nanomaterial, it is biocompatible, flexible and low-cost [Akb14, Akb15, Kop15]. Due to the good biocompatibility of graphene its application areas include e. g. biomedical applications, such as drug delivery into tissue, and biological sensing [Akb14]. In addition, graphene changes its properties when exposed to different gases, which makes it a promising antenna material for sensors detecting harmful or poisonous gases [Akb14, Kim15, Le12]. However, before graphene is ready to be implemented in high-volume manufacturing, it needs much further studying.

6 PHOTONIC SINTERING AND OTHER SINTERING METHODS

In general, sintering is a method, where thermal energy is transferred by some technique into metal or ceramic powders in order to make density-controlled materials [Kan05]. In this study, the metal powder, or metal flakes, spheres or particles of other form, are in liquid solution [Publications I–VII]. The aim in sintering is to establish an electrically conductive matrix by partially melting and fusing the adjacent conductive particles in conductive ink [All08], and this way to produce sintered structures with reproducible and aimed microstructure of the ready, sintered material [Kan05]. In addition to the formation of metallic contact between the conductive particles also the liquid phase solvents are evaporated during the sintering process [Ami12, Lee11b, Zen14], leaving only conductive particles left after sintering. The sintering process usually takes place in temperatures below material's melting point [Fal11, Fall12]. Even though the sintering process is done in temperatures lower than the materials melting point, the required temperatures are usually still quite high, too high for low-cost environmentally friendly substrate materials [Fal11].

When considering electronics manufacturing with electrically conductive inks there are nowadays multiple choices for sintering method, and they all have their benefits and drawbacks. Examples of the sintering methods are e.g. chemical sintering, laser sintering, plasma sintering, heat sintering, and photonic sintering [Nii14, Per12]. To all these different sintering methods the properties and form of raw material varies, and matching sintering process parameters are crucial in achieving the wanted microstructure [Kan05]. The properties of raw material, which vary, include e.g. chemical composition, powder particle size, powder particle shape, and particle size distribution [Kan05]. The process parameters include e.g. temperature, time, pressure, atmosphere, heating and cooling rate among many others [Kan05]. The process parameters depend on the sintering process.

The electrical properties of the sintered structures are extremely important to guarantee the proper electrical, and also mechanical, functioning of the device where the sintered part is used. Increased resistance of the ready sintered structure, or in other words poor conductivity, leads to unnecessary power losses in the ready-made device [Nii14]. This means excessive power consumption, causing too much heating, and also reliability problems can occur [Nii14].

Heat sintering is nowadays widely used sintering method with RFID additive manufacturing utilizing conductive inks [Nii14, Zen14]. However, this sintering method has some disadvantages, e.g. it is very slow when considering high-volume production, the heat sintering process can take over an hour, and it is not compatible with temperature-sensitive substrate materials [Per09, Wan13]. The requirements to use low-cost materials in high-volume production have created a need to develop other sintering methods for replacing heat sintering.

A selective sintering method is preferable especially in the case of heat-sensitive substrate materials. In selective sintering only the part that needs sintering, usually conductive ink area, is exposed to the sintering conditions, not the whole structure. This minimizes the damages caused by the sintering conditions to the other parts of the structure, which do not need sintering. Photonic sintering and heat sintering are examples of non-selective sintering methods, and laser, electrical and microwave sintering are examples of selective sintering methods.

6.1 Heat sintering

The traditional heat sintering of conductive inks requires high temperature and long sintering time [Kim09a, Wes12, Pol11]. The heat sintering equipment is usually bulky [Par13] and the device is energy consuming. The usual required temperature in heat sintering is about 250 °C for conductive inks, this high a temperature is unsuitable to most polymer materials [Fal11, Fal12, Lee11b, Par13] and other heat sensitive materials, as wood-based or textile materials. Some polymer materials, e.g. PI and polyarylate (PAR), can withstand these high temperatures [Fal11]. The main disadvantage of PI and PAR is their high cost [Fal11, Nii14]. In addition, when considering eco-friendly RFID tag manufacturing, the use of non-biodegradable polymers is not a good choice, even though they would tolerate the required process temperatures.

One drawback of heat sintering is that the whole structure is exposed to the sintering conditions [All08], in other words heat sintering is not a selective sintering method. Also the parts of the structure that do not need sintering are inside the oven. Hence, heat sintering is not an area-specific, or selective, method [All08]. In addition to the possible damage that the heat sintering produces to the areas which do not need sintering, energy is wasted because the volume to be heated is bigger than the actual needed volume to be sintered.

Furthermore, copper inks, and other conductive ink particle materials, which oxidize easily, need a vacuum or an inert gas atmosphere to avoid the formation of oxide layer on the conductive particles during the sintering process [Kim09a, Par14b, Pol16]. Copper oxide is electrically insulating, and consequently its formation has to be avoided during sintering process.

In this study heat sintering is used in [Publication VII] to compare this method with the very potential new sintering method, photonic sintering.

6.2 Photonic sintering

Photonic sintering is the most promising alternative to heat sintering in electronics manufacturing with conductive inks [Nii14, Zen14]. High intensity pulsed light from a xenon flash lamp is applied to a conductive ink layer in photonic sintering [Wes12]. The xenon gas is ionized in the lamp with high voltage, and after this the intense pulsed light is produced by a plasma arc between the electrodes inside the lamp [Kan11]. In other words photonic sintering uses the energy of intense pulsed light to sinter conductive ink; hence other name for this sintering method is intense pulsed light sintering (IPL) or sometimes high-intensity pulsed light sintering. Originally photonic sintering was developed especially for conductive inks with NPs [Wes12]. However, in this study, the possibilities of photonic sintering with regular screen printing conductive inks are studied, and these first results are very good [Publications I - V]. Photonic sintering is a very suitable sintering method also to other conductive inks than just NP inks [Publications I–V, Sch06].

Even though photonic sintering is not, in principle, a selective sintering method, it can be considered much more selective than e. g. heat sintering. Exposure of the whole device under manufacture to the high intensity light is not necessary in photonic sintering, but the area, where the light exposure is wanted, can quite well be determined with the use of an aperture mask. Thus, photonic sintering can be considered to be almost a selective sintering method.

The photonic sintering system consists of a xenon flash lamp, power supply, air cooling system and capacitors. In addition, there is user interface, where sintering parameters can be adjusted. The photonic sintering system, which is used in this study, is Xenon Sinteron 2010-L system [Publications I–VII]. In addition to the basic parts of photonic sintering system, in Xenon Sinteron 2010-L system there is also a mask under the flash lamp, with which the aperture can be adjusted. The aperture determines the size of the area to be exposed to a flash light. In the system used in this study the used dimensions of the aperture are 2 cm x 30 cm. A schematic picture of the basic principle of a photonic sintering system is presented in Fig. 17. In Fig. 17 there can be seen the flash light exposure as a cross-section, how the light from the xenon lamp is reaching the substrate, or more precisely the area on the substrate with the conductive ink pattern. A photo of Xenon Sinteron 2010-L is presented in Fig. 18. In addition to the basic parts of photonic sintering system, the equipment used in this study also has a conveyor table, which makes the alignment of the area to be exposed to the light easier and more precise [Xen13].

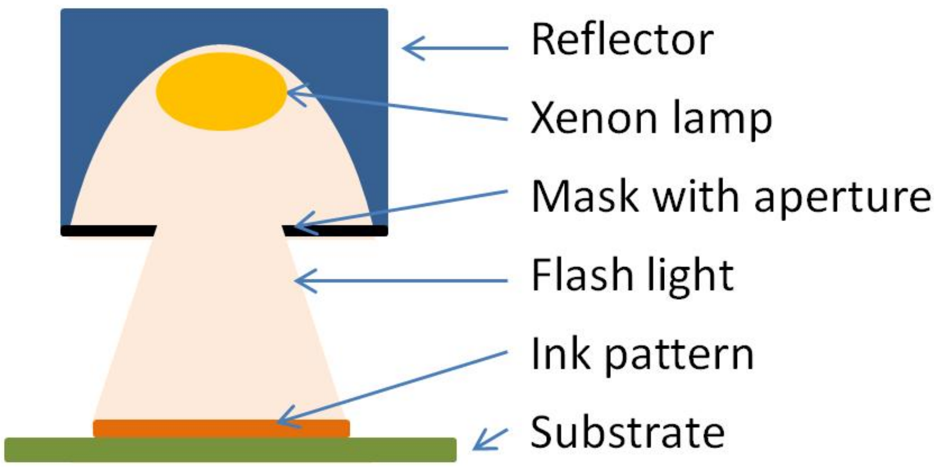


Figure 17 The principle of a photonic sintering system.

Figure 18 Xenon Sinteron 2010-L system which is used in this study.

The light spectrum from xenon flash lamp is broad [Kan11, Wes12], from ultra-violet (UV) to infra-red (IR) [Dra15]. The light energy is transformed to heat energy in the ink surface, and the conductive particles of the ink are sintered when they are heated through the light energy [Nii14]. It is known that the material's absorption of light can generate heat via non-radiative energy dissipation and exothermic photochemical reactions [Gu15]. The process time of photonic sintering is very short, only in the scale of micro- or milliseconds [Publications I–VII][Kan04, Par13]. The conductive inks are most often dark coloured, and the used substrate materials are usually light coloured, hence only the ink absorbs significantly light energy from flash pulse [Per12, Pol16]. This means that the ink is heated, but at the same time the substrate remains about in the same temperature as before the process [Nii14]. Even though the substrate does not absorb lots of energy from flash light, it warms up near the metal parts on its surface. The metal to be sintered heats up to a quite high temperature during photonical sintering, even though the time for heating is very short. Some of the heat energy from the conductive ink is conducted to the nearby substrate. Due to the very short process time of photonic sintering, the heat from conductive particles does not have time to transfer in significant level to the surrounding substrate material. This minimizes the heat induced damages to substrate, and allows the use of heat sensitive, preferably low-cost and ecological, substrate materials, such as wood-based materials, paper-based materials, low temperature polymers, and textiles [Sch06, Lim13, Wes12].

In the case where the substrate has quite similar light absorption rate with the conductive ink, also the substrate is heated and damages can be caused by the heating [Zen14]. Photonic sintering in an ink layer progresses from surface to inside of the ink layer [Lee11b]. This may be the reason for the need of multiple flash pulses in some cases. In addition this can cause problems, if the surface of the ink is well sintered, but residues of the unsintered ink are still inside the conductive pattern. This phenomenon is seen in this study in [Publication I], when the sintering energy has been too low for a good sintering result. When touching, or gently scratching, a surface of a sample with this phenomenon, the upper layer slides away and liquid phase ink can be seen underneath.

The main advantage of photonic sintering is the low-temperature process [Fal11] combined with the very short process time [Par13, Per12]. In addition, the basic concept of photonic sintering equipment can be quite compact compared e. g. to heat sintering furnace. However, the needed electrical power for the capacitors, which provide the needed high voltage to the xenon flash lamp, can result in quite a bulky equipment. Because of the very short process time copper, or other easily oxidizing materials, do not have enough time to form oxide on the surface of the conductive particles during the sintering process [Dha13]. Vacuum is not needed in photonic sintering of copper inks to avoid the oxide formation on the particle surfaces as in traditional heat sintering [Kim09a]. The very short sintering time of photonic sintering can prevent oxidation of copper particles even in room atmosphere [Kim09a, Wan13]. This is a great advantage considering manufacturing equipment, and also process cost. Every additional needed process condition increases the cost of the end product.

The photonic sintering is easily compatible with fast R2R technology [Fal11], the basic idea of this can be seen in Fig. 11. The photonic sintering equipment can be a part of the process line directly after the application of conductive ink, as seen in Fig. 11. The capability to fast R2R manufacturing and the possibility to use low-cost substrate and ink materials makes the photonic sintering very cost-effective sintering method [Wes12, Dra15].

In addition to special photonic sintering equipment, also regular camera flash light has been used for photonical sintering of NP inks in room atmosphere [Gu15]. The results of camera flash lamp sintering are promising, and a big advantage of this technology is the ease to reach the necessary equipment, and the small size of the equipment.

6.2.1 Sintering parameters in photonic sintering

The sintering parameters are found to be extremely important to the sintering result when using photonic sintering [Publications I–VII][Kan14, Ren14]. For example, the previously mentioned heating of the substrate during photonic sintering process, which can lead to minor damage in substrate, can be very well minimized with carefully chosen sintering parameters [Nii14]. Finding the threshold point that gives the best electrical properties without damaging the sample is important in photonic sintering process [Han11].

The photonic sintering has process parameters, which are presented in Table 6. The intensity of the flash light and the duration of the light pulse are the two parameters that affect most the degree of sintering [Wes12]. Lamp voltage is very often one parameter to be adjusted in sintering systems. The lamp voltage together with the time determine the energy of the light [Xen13]. There are also other parameters that affect the sintering result, such as number of flash pulses and aperture ratio. All the available parameters affect to the sintering result, and these parameters have to be optimised to every material combination individually [Publications I–VII]. This is extremely important with copper-based conductive inks, as is found in [Publications I–III, V–VI].

Different kinds of photonic sintering systems are available. At least sintering power can be adjusted in many of them. Usually this is done by adjusting sintering voltage and pulse length in the user interface. In many cases also the number of pulses, pulse frequency and aperture ratio are adjustable. The parameters, which can be adjusted in Xenon Sinteron 2010-L system, which is used in this study [Publications I–VII], are presented in Table 6 [Xen13]. With Xenon Sinteron 2010-L the period time includes one flash pulse and the time interval before the next pulse. The distance between the sample and the xenon flash lamp housing has been the same, 2.54 mm, throughout this study [Publications I–VII]. This is also the focus point of the used sintering equipment [Xen13]. In addition, the dimensions of the aperture (2 cm x 30 cm) have been the same throughout this study [Publications I–VII].

Table 6 General photonic sintering parameters and sintering parameters of Xenon Sinteron 2010-L system with their adjustability [Xen13].

Parameter	Allowable range in Xenon Sinteron 2010-L	Increment in Xenon Sinteron 2010-L
1. Pulse width	100 µs – 2000 µs	5 µs
2. Pulse width	100 µs – 2000 µs	5 µs
Width for continuous pulses	100 µs – 2000 µs	5 µs
Lamp voltage	1800 V – 3100 V	50 V
Pulse count	1 – 2000	1
Period time	0,1 s – 5 s	1 ms
Aperture ratio	10 mm – 80 mm	
Distance between sample and light source	25 mm – 76 mm	3.18 mm

Table 6 lists multiple parameters to be adjusted. The distance between the sample and the flash light influences on the impedance of the ready-sintered sample [Fal11]. The samples should be as close to the flash lamp as possible to achieve the best results [Fal11]. However, if the distance between the sample and the flash lamp is decreased too much, the absorbed energy can be too high damaging the substrate [Fal11]. It has been found that if samples are overexposed to xenon lamp, thus if too much energy is applied on the sample, the sample is damaged and its electrical properties are worsened [Lim13].

The energy of each flash pulse can be calculated using the following formula:

$$E = (\frac{V}{3120})^{2.4} \cdot t, \tag{9}$$

where E is the energy in Joules per pulse, V is the voltage in Volts and t is the time in microseconds [Xen13]. This is the energy that the lamp produces. In this study there has been an aperture mask under the flash lamp, and therefore only a portion of the light generated reaches the target to be sintered [Publications I–VII]. However, when investigating the results of this study, the aperture has been the same throughout all the samples in all the publications, as has also been the distance between the lamp and the sample, so the proportion of the energy focused on the substrate is the same with every sample in relation to the total lamp energy produced.

Preheating of the sample is done before the actual photonic sintering e. g. in studies [Par13, Pol16]. The purpose of the preheating is to reduce the amount of liquid solvents in the antenna pattern area before actual sintering [Par13, Pol16]. The liquid solvents evaporate in photonic sintering process, and if the sintering energy is too high, pores are induced because of rapid solvent evaporation. Hence, the reduction of liquid solvents makes the photonic sintering process more tolerant to sintering parameter variations, in other words, it gives more tolerance in the parameter determination. However, the preheating is one additional process step, which takes time and equipment, and hence it is not recommendable in high-volume low-cost R2R manufacturing. Photonic sintering can very well be done without preheating [Publications I–VII].

In addition, when thinking of fast R2R manufacturing, the number of flash pulses should be kept in minimum, preferably in only one pulse. The need of multiple pulses leads to process slowdown because of the time needed for the sintering system capacitor to charge between pulses [Kan14]. Even though this time is not in macroscopic level long, in Xenon Sinteron 2010-L system it is 98 ms minimum [Xen13], when comparing it to the time requirement for one pulse (micro- or milliseconds), the increment is huge. However, the aim towards only one flash pulse needs fine-tuning of sintering parameters [Kan14], as seen in [Publication I].

6.2.2 Photonic sintering of nanoparticles

Because of the lowered melting temperature of NPs, the photonic sintering of NPs is a bit easier than sintering of the same bulk material [Kan14, Per12, Sch06]. The lowered melting temperature of NPs is due to the high surface-to-volume ratio [Lai96, Per12, Sch06]. It has been shown that with photonically sintered silver NP inks 84 % of the density of bulk silver can be reached [Wes12]. This is quite a good level, and it is perfectly enough in most of the RFID applications. The resistance of photonically sintered silver NP inks is found to be slightly higher than the heat sintered counterparts [Lee11b]. This is also seen in this study in [Publication VII], where the photonically sintered tags with silver NP ink on PI substrate has slightly lower read range than that of the heat sintered counterpart. In addition, it has been found that there is an optimum lamp voltage, and beyond this voltage silver NP film is damaged by blow-off or cracking [Wes12]. In this and other studies, a lot of different tests have been done with silver NP ink on different substrate materials [Publication V–VII].

In general, it has been found that the photonic sintering of copper inks is much more difficult than the photonic sintering of silver inks [Ren14]. This applies to both, NP inks as well as regular screen printing inks, and this is seen also in this study [Publications I, V, VI]. The sintering parameters are harder to define to copper-based inks, the allowed tolerances with them are much smaller than with silver inks [Ren14][Publications I, V, VI]. This applies to both, the NP inks as well as to regular screen printing inks [Publications I, V, VI].

Copper NPs are very good light absorbers because of their very high surface-to-volume ratio [Kim09a] and dark colour. It has been found that the resistivity of a photonically sintered copper NP ink reduces with an increasing light energy [Nor15]. However, too high energy can damage the substrate, or cause blow-off in the antenna. It has been found that the oxide shells covering the copper NPs is completely reduced in the flash light irradiation leading to copper result [Joo15, Sug15]. The mechanism behind the reduction of copper oxide to pure copper in photonic sintering is not yet clarified thoroughly [Kan14].

6.2.3 Photonic sintering of screen printable inks

Photonic sintering of screen printable silver inks can be done quite easily, even though the photonic sintering process has originally been developed especially for NP inks. The same process with different sintering parameters can be applied to both screen printable and NP inks.

The silver inks, both NP as well as screen printable inks, have quite a good tolerance in sintering parameters [Publications I, V, VI], in other words the silver ink sintering allows variability in sintering parameters, at least to some extent. However, also with screen printable silver inks too high or too low sintering power causes damages and lowered performance in the conductive pattern [Publication I]. These phenomena have been seen in this study with regular screen printing inks, with both silver and copper oxide screen printing inks [Publication I]. Photos of samples with the blow off phenomenon are in Fig. 19 c and d. In these photos it can clearly be seen how the conductive ink layer has been blown off from the substrate surface due to excess energy from xenon flash lamp.

The importance of careful determination of photonic sintering parameters applies also to regular screen printing copper oxide inks [Publications I - III]. In [Publication I] it is found that if the flash pulse energy is too low with the first flash pulse when using copper oxide ink, the conductivity of the ready-made antenna is not good. The energy delivered to the system with following flash pulses does not improve the antenna conductivity significantly [Publication I]. This indicates that the sintering parameters of the first flash pulse are the very significant factor in the performance of a ready-made antenna. Photos of RFID tags manufactured with copper oxide screen printing ink on cardboard and wood substrates are in Fig. 19 a and b. In these photos a and b the sintering energy has been too low, residues of unsintered conductive ink can be seen in the antenna pattern area. On the other hand, if the energy of the first flash pulse is too high, the antenna is damaged with blow off phenomenon, as seen in Fig. 19 c and d.

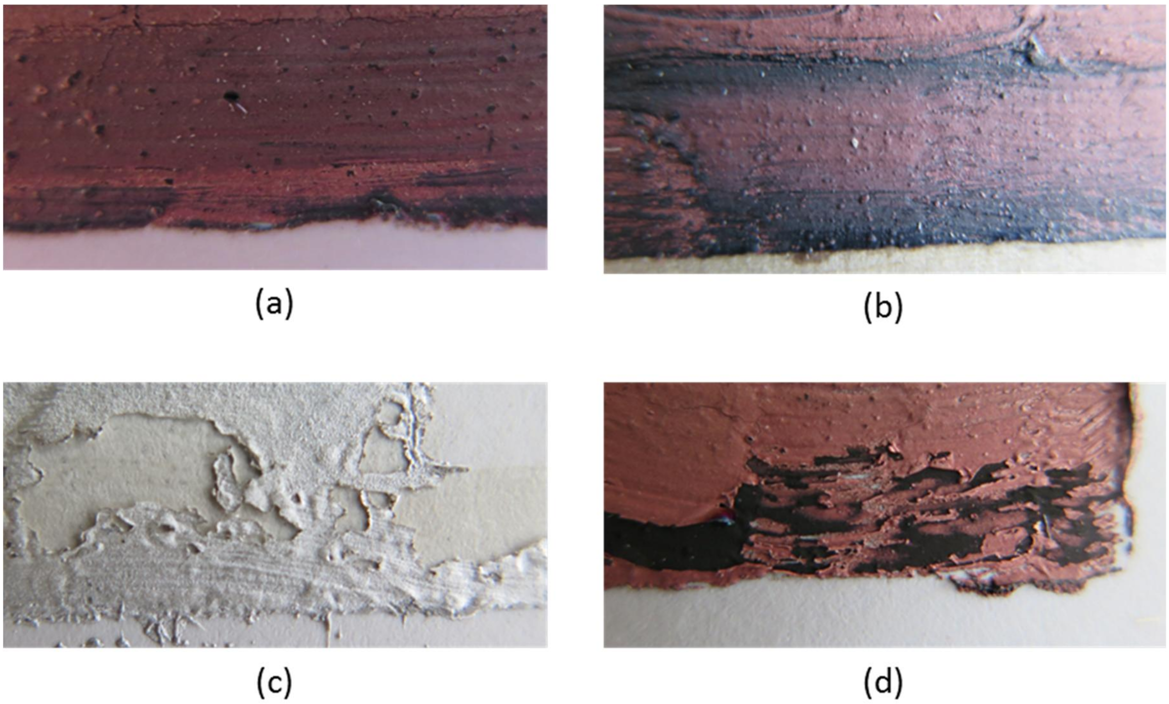


Figure 19 Photos of photonically sintered tags:
a) Cu on CB substrate, too low sintering power.
b) Cu on Wood substrate, too low sintering power.
c) Ag on CB substrate, too high sintering power.
d) Cu on CB substrate, too high sintering power.

6.3 Other sintering methods

Many other possibilities for sintering RFID antennas manufactured with conductive inks exist in addition to heat sintering and photonic sintering. All of them have their benefits and drawbacks, and they have their own application areas where they suit very well. Here are some of them briefly introduced.

Plasma sintering uses low-pressure Argon plasma irradiation [San15, Sug14]. Plasma sintering progresses from top to bottom, and the required sintering time depends on the conductive ink layer thickness [Nii14]. Plasma sintering is a slow sintering method possibly taking hours depending on the thickness of the sample [Nii14]. Another problem with plasma sintering, associated with the top to bottom progression, is that if the sintering time is too short, the bottom layers of the sample are left unsintered, and this way the adhesion to the substrate is very poor

[Nii14]. The very long process time makes plasma sintering unsuitable for high-volume production.

Laser sintering heats the area exposed to the laser beam for a very short time [Nii14]. Laser sintering is a selective sintering method, where only the small antenna pattern area exposed to the laser beam is sintered [Kum11, Lee14]. Despite the very short exposure time, the temperature may rise temporarily quite high in the exposed area, and low-temperature substrate materials, like PET, cannot withstand it [Nii14]. One problem related to laser sintering is that the laser beam is much smaller than the total area to be sintered [Kim09a, Nii14]. The use of laser sintering requires multiple passes over the pattern to be sintered [Lee11b, Nii14], and this slows down the process remarkably. When the substrate is transparent to the laser wavelength the laser beam does not harm the substrate material, when it is swept across it [Nii14]. One disadvantage of laser sintering is that very often the unsintered ink material has to be removed after sintering, for instance by washing and rinsing [Zen14]. This adds process steps and thereby also manufacturing costs. One benefit of laser sintering is its ability to form very precise conductive patterns with very small dimensions [Zen14]. In general, the special properties of laser light, such as coherence and possibility to very focused light exposure, are not needed in RFID antenna sintering [Sch06]. In addition, laser is a very expensive source of light [Sch06]. Hence, when low-cost high-volume R2R manufacturing is considered, laser sintering is probably not the choice for sintering technology.

There are two ways to do electrical sintering, one is to apply DC voltage over the deposited conductive ink, and the other is to use an alternating electric field [All08]. The DC voltage leads to current flow inside the ink material, causing local heating of conductive particles [All08]. This sintering method is fast, it takes only milliseconds [All08]. The benefits of this sintering method include: substrate does not warm up significantly because the heating occurs locally in conductive ink, short sintering time and the possibility to see the sintering result during the process [All08]. However, this sintering method requires ohmic contacts to the ink layer [All08]. The use of alternating electric field eliminates the need for ohmic contacts [All08].

In microwave sintering the conductive metal particles are heated with microwave radiation [Per09]. Only the metal particles absorb the microwaves, whereas the substrate material is usually transparent to microwave radiation [Per09]. Microwave sintering is fast, but the thickness of the sintered layer is quite restricted because of the small penetration depth of microwaves [Pol11]. However, when considering e. g. inkjet printed RFID tags operating in microwave region, thick enough conductive layer is probably achieved.

UV-radiation is used to sinter conductive structures in UV-sintering method [Pol11]. The patterns made with conductive inks are put into an UV-oven [Pol11]. Usually one sintering round is not enough, but multiple sintering rounds are often needed for good conductivity [Pol11]. The substrate temperatures in UV-sintering are generally lower than in heat sintering, but they are not very low [Pol11]. For instance substrate temperatures of about 55°C to 110 °C have been observed

[Pol11]. These kinds of substrate temperatures are too high for low-cost temperature-sensitive materials, such as paper-based materials. UV-sintering method is not selective, thus the substrate material should be chosen so that UV-radiation does not cause harm to it. This method is easily applicable to R2R manufacturing [Pol11].

7 RFID IN SENSING APPLICATIONS

In addition to identification purposes, passive RFID technology can be utilized also in sensing applications. This topic has gathered increasing interest in recent years [Dei13, Fer15, Fer16], especially with applications requiring low-cost ubiquitous wireless sensing [Bha10]. Battery-free, embeddable, implantable or wearable sensors can be done using passive RFID technology [Mar10, Yea10]. Passive RFID based sensors get all the needed energy from the RFID reader [Sam08]. Thus their operation life time is not limited by the battery properties [Sam08]. In addition, these passive RFID sensors have small size and they are very light in weight [Kha14, Yea10]. These properties make the passive RFID sensing and identification tags very interesting in applications, where the tag should be embedded permanently in some object [Sam08]. The need for a reader to be in the proximity of the tag is a limiting factor when using passive RFID sensors [Sam08]. The price level of passive RFID tags with sensing capability should be in the same level with regular RFID identification tags, even though they offer more functionalities to the end user [Sam08], in order to expand their usage.

On the other hand, active RFID tags offer very good possibilities for sensor applications, since they have an on-board power supply and very long operating distance [Mar10, Sam08]. Many wireless sensing applications already in use utilize battery-powered sensors [Bha10]. However, the power supply, usually battery of some kind, requires space on the tag, increases significantly the weight and cost of the tag [Bha10], and the maintenance of the battery is difficult [Mar10, Sam08]. Due to these drawbacks this thesis concentrates on fully passive identification and sensing with RFID tags.

Knowing of variables such as temperature, acceleration, applied force or humidity of an item, or possible contamination of harmful agents or bacteria, would be beneficial in many applications [Fer15, Mar10, Wan04]. Often, e. g. with temperature sensing, it is enough to know, if a certain threshold level is exceeded [Wan04, Wan06]. If this is for instance in grocery transportation, the right actions can be proceeded. The RFID based sensing in these kinds of cases is very beneficial, because the sensor data can be read without line-of-sight, and without unnecessary moving of items e. g. in a truck. However, in many cases it is important to know the level of a variable, not just the threshold information.

The RFID based sensing is expected to be an important platform in ubiquitous sensing [Jia08, Kha14]. It gives great possibilities in the era of the IoT, enabling simultaneous identification and sensing of different quantities [Mar10]. The use of different sensing materials combined in a low-cost RFID tag enables new, innovative means for remote, passive and wireless sensing [Jia08]. One other very interesting utilization area of passive RFID sensing is human sensing, especially implanted sensors [Mar10]. This study area is under intensive studying, but in this thesis the implantable passive RFID tags are not studied.

7.1 Categories for realization of RFID based sensing

There are two basic categories to realize sensing in an RFID tag [Cha07a]. One is to add special sensor element or sensor elements on the tag, and the other is to use normal RFID identification tag itself as a sensor element [Cha07a, Mar10]. The principles of these two categories are presented in Fig. 20.

In the approach that uses normal RFID tag structure as a sensing element, some physical phenomenon of interest changes the tag's electrical properties, for instance antenna's impedance and gain can be changed according to the measured variable [Bha10, Mar10], hence tag's peak frequency or peak read range can change according to this [Fer15]. The antenna impedance changes according to the changes in the dielectric materials surrounding it [Bha10], and this phenomenon can be utilized in RFID based sensing.

In principle, there are two ways for establishing the sensing function in this category. First, a change in the quantity of interest induces mismatch of the IC impedance and the antenna impedance [Bha10]. This leads to the reader requiring to transmit additional power to turn the tag IC on [Bha10]. The difference in the transmitted power can be utilized in sensing [Bha10]. Second, for a given transmitted power the impedance mismatch between IC and antenna causes reduction of the transmitted power from the reader to the IC, and this leads to a reduced backscatter power from the tag to the reader [Bha10]. Thus, the change in the backscattered power can be used in sensing [Bha10]. An advantage of these approaches is that no additional electronics is needed, which may be advantageous in low-cost applications [Cha07a]. In addition, these approaches provide compactness of a tag [Cha07a].

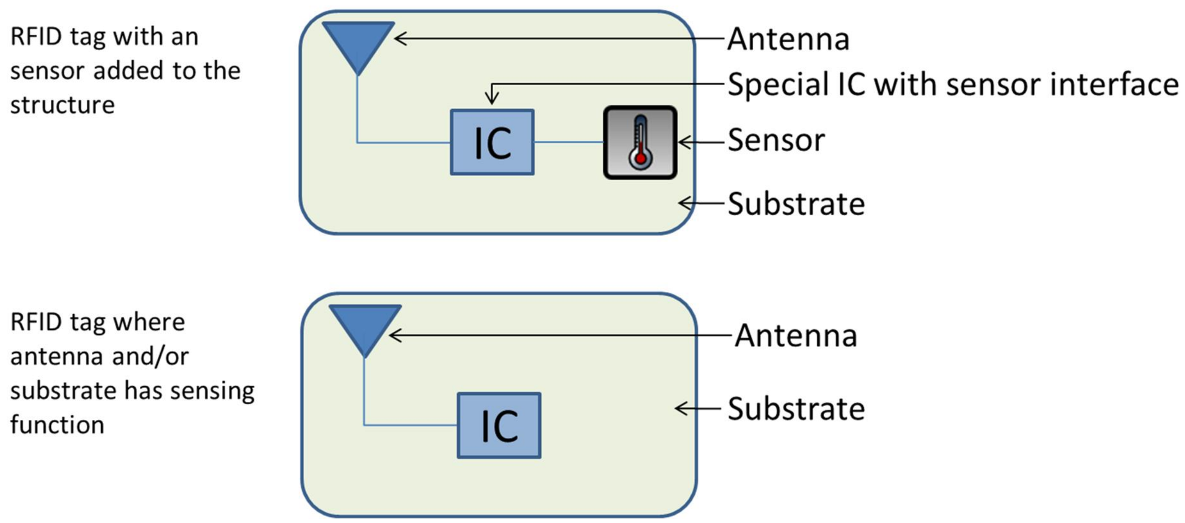


Figure 20 The two categories of RFID based sensing.

If additional sensors are used on the tag for sensing purposes, it increases the tag and IC complexity, and usually tag price increases [Cat13, Fer15]. The IC might contain the sensor elements and functions [Cat13], or it has to have functions which enable the information collecting from the separate sensor on the tag. In some applications there can be multiple ICs on a tag, one for regular RFID identification use, and one or more for sensing purposes [Mar10, Smi05]. In addition, miniaturization of a tag is more difficult because the sensor takes space in the tag structure [Cat13, Cha07a]. Furthermore, additional sensors add the total energy consumption of the RFID tag [Cat13]. The design of sensor and its usage has to take into account that there is no power continuously available in a passive RFID tag [Wan04]. The RFID tag is powered only at the time of communication with the reader [Wan04]. This means that most of the time the tag is unpowered. In addition, when the tag is powered, the available energy is very small [Wan04]. One possibility is to use some kind of energy harvesting technology as a secondary energy source together with tags of this category [Sam08]. Possible energy harvesting methods include e. g. kinetic, solar and thermal energy harvesting possibilities [Sam08]. However, the energy harvesting increases the complexity, price and weight of the tag. On the other hand, there are nowadays components available with very low energy consumption, enabling the use of this category RFID based sensing [Sam08]. Due to the drawbacks with this category, especially the higher cost and increased complexity of passive RFID tags, this category of RFID based sensing is not beneficial when considering low-cost high-volume production of UHF RFID tags for identification and sensing applications.

7.2 Humidity sensing

Especially humidity sensing is interesting, when thinking of the application areas of RFID tags on wood-based substrates. The humidity level is often very important to know for instance inside structures of houses and in logistics chains. The humidity level, together with the ambient temperature, affect in a great extent the level of comfort, productivity and human health indoors [Jia08]. Hence the humidity level has great effect on cost-savings, gained with both the health issues together with better work productivity. Nowadays the humidity level inside wooden structures cannot be easily measured without invasing the structure. This means lots of work both in the measurement phase as well as in the phase of repairing the damages caused by the traditional humidity measurements. The decision to do these kinds of invasive measurements is often made in the stage, when there are already major problems e. g. in human health. One non-invasive possibility is to use humidity sensors with batteries embedded into structures. However, this approach requires battery changing every now and then, and the battery changing needs invasing the structure. The possibility to measure moisture inside structures wirelessly and without the need of battery gives means for early stage detection of moisture induced harms, and this way money is saved and human well-being is increased.

Most often humidity sensors measure the relative humidity (RH) and not the absolute humidity [Den14]. Relative humidity is the ratio of the moisture level compared to the saturated moisture level in the same temperature and pressure conditions [Den14]. RH is expressed in percents [Den14].

Humidity sensing with passive RFID tag without additional on-board sensor has been done in [Jia08, Vir11]. In this study the possibilities of humidity sensing with wood substrate RFID tags are studied [Publications II, IV]. Normal RFID tag is used as a sensing element in these studies. The idea is based on that water, or moisture, near an RFID antenna causes ohmic losses in the antenna [Jia08]. In addition, moisture absorbed in the substrate changes the relative permittivity and loss tangent of the substrate [Mon99]. The resonance frequency and read range of the antenna changes due to these water induced changes in the tag [Jia08]. The moisture level induced changes in the read range and peak frequency of the tag allow that the information of moisture level can be achieved without special sensor integrated on the RFID tag. In [Publications II, IV] plywood is used as a substrate material. Plywood, and wood in general, absorbs easily water, and this water uptake is proportional to the surrounding humidity level. Hence, the water very near the antenna, absorbed into the substrate, is affecting the tag performance [Jia08][Publications II, IV]. One nowadays commonly used material in humidity sensors is PI because of its quite good water uptake and suitability to normal manufacturing technologies [Den14]. However, wood-based substrate materials are eco-friendly, making them a very interesting substrate choice for humidity sensing applications.

The results in [Publications II, IV] show that silver inks on plywood substrate enable particularly well humidity sensing. This gives great start to study further this application area. The silver ink manufactured RFID tags in [Publication IV] did not even need a coating in order to function as a humidity sensor. Photos of non-coated UHF RFID tags manufactured using silver screen printable ink on plywood can be seen in Fig. 21. The upmost photo is of a tag which has been 1 h in 100% RH, the middle photo is of a tag which has been 5 min in 100% RH and the lowest photo is of a tag which has not been in RH at all. From the silver ink manufactured samples in Fig. 21 no clear changes can be seen, thus they tolerate moisture well enough, even without coating. However, in [Publication II] it was found that the copper oxide ink manufactured RFID tags do not tolerate moisture in good enough level in order to make possible humidity sensing, or reliable identification, in moist environments. However, different kinds of coatings on copper antenna utilizing RFID tags could be an aspect worth further studying, even though the results with glue coating in [Publication II] were not very promising. The coating of the tags with copper antenna did not increase the reliability of the tags to moist environment to a good level [Publication II]. Photos of non-coated copper oxide ink manufactured UHF RFID tags on plywood substrate are seen in Fig. 21. The upmost photo is of a tag which has been 1 h in 100% RH, the middle photo is of a tag which has been 5 min in 100% RH and the lowest photo is of a tag which has not been in RH at all. From these photos in Fig. 21 the moisture induced degradation can clearly be seen. The tag, which has been 1 h in 100% RH, has very clear ink spread in the antenna edges. Similar phenomenon can be seen with the tag which was 5 min in 100% RH, but in this case the ink spread is slightly smaller. Thus the copper oxide manufactured tags have not tolerated moist environment well.

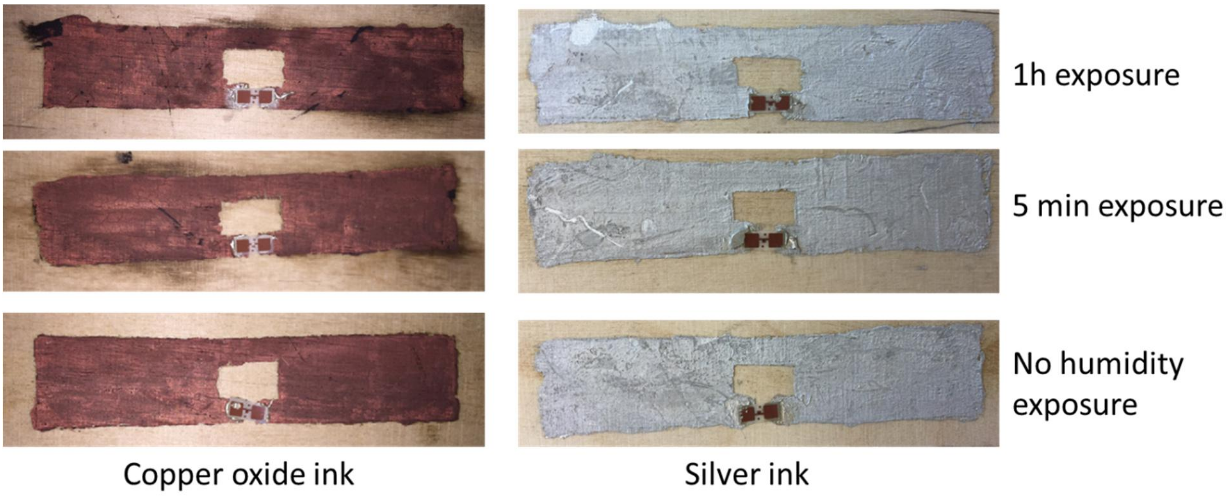


Figure 21 Copper oxide ink and silver ink manufactured UHF RFID tags on plywood substrate after 1 h and 5 min exposure to 100% RH, and without RH exposure.

7.3 Sensing of other quantities

In addition to humidity sensing, also other quantities can be sensed using RFID tags. Some examples of RFID-based sensing of these other quantities are briefly presented in this section.

Temperature sensing is very important for instance in pharmaceutical and food supply chains, in hospitals and in different industrial processes [Mar10]. When the threshold information is enough, the measurement can be done with a seal or fuse [Mar10]. One possibility is to embed a shape-metal-alloy (SMA) conductor on the tag [Mar10]. When the temperature exceeds a certain value, the SMA conductor changes its shape, and this shape change can be engineered to permit or prevent the IC responding to the reader [Mar10]. In addition, when RFID technology with additional functions in a chip is used, there can be a temperature sensor interface in the special IC. This approach needs e. g. resistors on the tag for temperature measurement [Fer15]. Furthermore, there can be a temperature sensor embedded directly on the IC [Fer15].

Displacement has been measured using passive RFID tag [Bha09]. This application is based on the fact that when metal is near an RFID tag the metal changes tag’s response to reader [Bha09]. The degradation of RFID performance is utilized to directly quantify displacement [Bha09]. This approach needs a metallic plate to be attached to the object whose displacements is to be measured [Bha09].

Strain sensors have been done with UHF RFID tags and chipless RFID tags [Kim14, Lon15]. The idea of the chipless sensor RFID tag is that when the metal antenna on RFID tag is stretched its resonance frequency changes [Kim14]. The RFID tag has an inductor and a capacitor establishing an LC-circuit [Kim14]. The resonance frequency of the LC circuit changes according to the strain applied on the tag [Kim14]. In the regular RFID tags in [Lon15] the strain sensing of the tag is based on utilizing stretchable conductive fabric. The antenna is manufactured from non-stretchable conductive fabric with a section of stretchable fabric included [Lon15]. The antenna impedance changes according to the strain applied to the RFID tag, because the dipole antenna elongates [Lon15].

7.4 Conformal coating of RFID tags

Conformal coating is needed especially in cases, where electronics are exposed to humidity, end even more if the substrate material is highly water absorbent. Many environmentally friendly materials, like cardboard, paper and wood-based materials have high moisture absorption capability. In addition to possibly being a helpful property in humidity sensing applications, this potentially establishes a need for coating of the tag to avoid moisture induced reliability problems.

In addition to moisture, also mechanical stresses can be involved with the RFID tags in field use [Kel12]. These mechanical stresses include e. g. wear and tear [Kel12]. Coating of an RFID tag reduces the effect of mechanical stresses to the tag functioning and operating life. In addition, also light, especially sun light, can degrade the tag. Many substrate materials, e. g. many polymers, paper- and wood-based materials, degrade due to the UV radiation of sun light [For95, Xen13]. This light exposure induced degradation of the tag can be minimized using proper conformal coating of the tags.

There are five conformal coatings that are often used to protect electronics: epoxy, silicone, acrylic, polyurethane and parylene [Hal11, Kel12]. Especially epoxy, and in general epoxy-based materials, is widely used. Epoxy is a thermosetting material, it is easy to handle and it is relatively cheap [Jun15]. The mechanical properties of an RFID tag can become better with an epoxy-based coating, if the used substrate material itself has not very good mechanical properties [Jun15].

A regular textile glue Gutermann Creativ HT2 was used as a conformal coating of the tags in this study [Publications II, IV]. In [Publications II, IV] it was found that the coating increased the tag's tolerance against moisture induced changes in performance, and this way probably also resulted in increased reliability. However, when considering RFID tag as a humidity sensor, the coating of the silver ink manufactured tag was not beneficial [Publication IV]. In this case the tag's sensitivity to moisture was better without coating [Publication IV]. In the case of tags manufactured with screen printable copper oxide ink not even the glue coating prevented the humidity from significantly affecting the tag performance, and probably also the tag reliability [Publication II]. This ink-substrate combination requires other coating materials, and much further research work, before it could be used in high-humidity environments [Publication II]. However, in atmospheres without excessive humidity the RFID tags manufactured with copper oxide ink perform well enough offering a very low-cost alternative for more expensive silver ink manufactured tags [Publication II].

The conformal coating of RFID tags increases the complexity of the manufacturing process [Publications II, IV] and cost due to the increased manufacturing process steps together with additional material need. Hence, the use of conformal coating in low-cost high-volume RFID tag manufacturing should be avoided, if possible. However, in some applications and environments the benefits of the conformal coating exceed the disadvantages, and they should be used in order to guarantee the reliability of the tags in field use.

Even though the basic idea in the use of passive RFID tags as sensors is quite simple, there are still very many issues to be studied. For example, long-term reliability is an issue to be addressed in the future research work, the use of accelerated reliability testing would significantly increase the knowledge of long-term reliability of the tags. One another thing is to study the selectivity of an RFID based sensor against other environmental conditions than the measured variable, how they affect the tag performance. In addition, further study is needed to find out, how the varying reading distance affects to tag functioning, and how surrounding objects affect to the tag performance [Fer15]. However, even though there are still many issues waiting for research, the sensor functions with RFID technology offer great future possibilities.

8 CONCLUSIONS AND FINAL REMARKS

The photonic sintering process in UHF RFID tag manufacturing is a very good choice when considering environmentally friendly, low-cost, high-volume manufacturing. This technology enables the manufacturing of huge amount of RFID tags for the new era with the IoT. The massive need for identification and sensing applications in the IoT can be satisfied with brush-painting, or screen printing, of conductive inks, and then sintering the manufactured patterns via photonic sintering. This process is very well suited to low-cost eco-friendly substrate materials, which are needed in future RFID applications. Furthermore, the IC should be interconnected to the manufactured structure using flip chip technology. When thinking about the reliability aspects, or RFID tags utilized in sensing applications, coating of the ready-made UHF RFID tags can be beneficial.

In this study both NP and regular screen printable conductive inks have been used. In the application area intended in this study, eco-friendly low-cost high-volume RFID manufacturing, the use of NP inks does not give any benefit compared to regular screen printable inks [Publication I]. NP inks are much more expensive than screen printable counterparts, they are much harder to handle in manufacturing process, and the special properties of them, ability to do very thin and precise conductive patterns, are not needed in the application area of this study.

In the application area of this study the antenna design has to be made according to the manufacturing process, the antenna design cannot be optimized for top electrical antenna performance. However, even in these kinds of applications, low-cost high-volume manufacturing, the antenna performance with the electrically non-perfect antenna design is perfectly good enough [Publications I–IV, VI, VII]. The read ranges are very sufficient to most of the nowadays and future RFID identification and sensing applications [Publications I–IV, VI, VII]. Even though the copper oxide ink as the conductive ink material in this study is not reaching the performance level of silver ink counterpart, the performance level of copper oxide ink manufactured RFID tags is very good in normal room atmosphere [Publications I–III]. When the cost issues are in a major role, the use of copper oxide ink is the best choice for future environmentally friendly low-cost high-volume RFID manufacturing for the IoT.

This study has been mostly experimental, researching the possibilities of new materials and processes for green high-volume R2R RFID tags. The results are very promising. However, there are still many issues that need studying, such as long-term durability and reliability aspects.

The results in this study show that environmentally friendly, low-cost, high-volume UHF RFID tag manufacturing can be done with the approach presented in this study. In addition, the humidity sensing results with screen printable silver ink on wood substrate show that this approach can be utilized in many applications. The material and manufacturing method combinations presented in this thesis outline the future for green UHF RFID identification and sensing manufacturing.

8.1 Short summaries of the results from the publications

In the following paragraphs the main results of the publications of this thesis are summarized. Reverse order of publications is used in this summary, because the research work of this thesis proceeds in that order.

Publication VII, entitled ”Effect of Sintering Method on the Read Range of Brush-painted Silver Nanoparticle UHF RFID Tags on Wood and Polyimide Substrates”, studied the possibilities of brush-painting together with photonic sintering for the first time. Photonic sintering was compared with heat sintering. In addition, for the first time wood-based substrate material was used, and the results with it were compared to those with polyimide substrate counterparts. The results of this publication show that the photonic sintering and wood substrate are very potential method and material for eco-friendly high-volume production of UHF RFID tags. Even though the read range results are better with polyimide substrate than with wood substrate, the wood substrate results are also good. The peak read range with wood substrate is about 5 meters, which is sufficient for many UHF RFID utilizing application areas.

Publication VI, entitled “Experimental Study on Brush-Painted Metallic Nanoparticle UHF RFID Tags on Wood Substrates”, introduced copper-based conductive ink materials on wood substrate to be used with brush-painting and photonic sintering. Sample tags manufactured with copper NP ink were compared with NP silver ink manufactured counterparts. The results show that functioning UHF RFID tags can be manufactured with both the inks. However, the read range results are not very good, especially not with copper NP ink. The peak read ranges of copper NP ink manufactured tags were about 3.5 meters and for silver NP ink manufactured tags almost 5 meters. The results of this publication were promising from the manufacturing method and substrate material point of views, and they lead this thesis work to exploit regular screen printable conductive inks.

Publication V, entitled “Parametric Optimization of Inkjet Printing and Optical Sintering of Nanoparticle Inks”, concentrated on the possibilities of photonical sintering of NP inks. Both silver and copper NP inks were used. The optimal inkjet printing and photonic sintering parameters were searched for these material combinations. The results were good showing that these materials and manufacturing methods are suitable for UHF RFID manufacturing, especially the suitability of photonic sintering was in the interest of this thesis work. In this publication the substrate material was well-known PI, which is not an eco-friendly material choice. In addition, the inkjet printing is not a very fast manufacturing process, hence it is not suitable to high-volume manufacturing. Based on the results of this study the thesis work continued towards more environmentally friendly substrate materials and higher-volume capable manufacturing process.

Publication IV, entitled "Experimental Study on Brush-Painted Passive RFID-Based Humidity Sensors Embedded into Plywood Structures", concentrated on the possibilities of using passive RFID tag without any extra circuitry or on-board sensors as a humidity sensor. The idea was to utilize the good moisture absorption of a plywood substrate affecting the antenna performance for detecting different humidities. The UHF RFID tags were manufactured using regular screen printable silver ink on plywood substrate using brush-painting combined with photonical sintering. The effects of conformal coating on tag sensing capability and reliability in high-humidity environment were also studied. The results show, that this approach is very promising for making fully passive UHF RFID based humidity sensors that can be e. g. embedded inside different structures. The humidity absorbed from the environment inside the plywood affected to the antenna performance of the uncoated tags, and this can be used to derive humidity data from the target. However, the conformal coating of tags prohibited them from working as humidity sensors, but the coating increased the tag reliability in moist environment significantly. Hence, when the reliability in humid environment is in the focus point, the coating of the tags should be considered.

Publication III, entitled "Additive manufacturing of Antennas from Copper Oxide Nanoparticle Ink: Toward Low-Cost RFID Tags on Paper- and Textile-based Platforms" focuses on brush-painting and 3D direct write dispensing of regular screen printable copper oxide conductive ink on textile and cardboard substrates. The results show that the tag performance on both the substrate types and brush-painting together with photonical sintering is in a good level, peak read ranges are over 6 meters. This is enough for numerous IoT and identification applications. However, the 3D direct write dispensing with these material combinations did not perform as well as brush-painted counterparts. The peak read range with 3D printed sample was over 3.5 meters. This read range level is sufficient to many applications, but it also indicates, that further studying with this printing process and material combination is needed. Hence, the much simpler brush-painting is beneficial in this application area compared to 3D direct write dispensing. The authors want to point out that there is an error in the title of this publication. The used conductive ink in this study is regular screen printable conductive ink, not NP ink, even though the publication title says so. This error was unfortunately unnoticed throughout the writing and publication processes, it was noticed when the author began to prepare the conference presentation.

Publication II, entitled "Reliability of Passive UHF RFID Copper Tags on Plywood Substrate in High Humidity Conditions", studied the possibilities of constructing a humidity sensor using passive RFID tag manufactured with regular screen printable copper oxide ink on plywood substrate. In the passive UHF tag there were not any additional parts on-board, the idea was to use the effect of the moist plywood to the antenna performance for humidity sensing. In addition, the effect of tag coating for the humidity sensing, and on the other hand, on the reliability of the tag in moist environment, was studied. This method has been used successfully with silver screen printable ink in Publication IV. However, the results show that the copper oxide ink on plywood does not withstand the high humidity conditions used in this study. Not even the conformal coating protected the tags well enough against the 100% RH. Hence, this approach is not suitable to humidity sensing, at least not in the very high humidity conditions as in this study. However, these tags are very suitable for normal identification purposes in regular environments.

Publication I, entitled ”Brush-painting and Photonical Sintering of Copper Oxide and Silver Inks on Wood and Cardboard Substrates to Form Antennas for UHF RFID Tags”, describes a thorough study about the photonical sintering parameters of regular silver and copper oxide screen printable inks. The UHF RFID tags manufactured with copper oxide and silver inks on wood and cardboard substrates were compared. The results confirmed that the photonical sintering parameters need to be chosen according to the materials, substrate and conductive ink material, combination used in the application, and that the tolerance of the variance in photonic sintering parameters is higher with silver screen printable inks than with copper oxide screen printable inks. In addition, it was found that the regular screen printable inks performed better than NP inks with the materials and processes used in this study. Hence, the use of NPs does not give any benefit in this application area. All the read range results with the best sintering parameters in this study are in a good level, peak read ranges of all test samples are over 8.5 m, which is well enough for normal identification and sensing applications.

8.2 Future work

Even though the results with electrically conductive silver ink on wood substrate are very good, the tests conducted here were only the beginning in the field of reliability issues. In addition, the copper-based conductive inks need strong further research work in the field of reliability issues. However, copper is a very promising conductive ink material possibility, so it is definitely worth for further studying.

In this study the ICs are joined to the antenna with a strap. However, the nowadays widely used flip chip interconnection method in RFID high-volume manufacturing would be a very interesting study topic in the near future. The flip chip technology is well known, but with these kinds of new material combinations as used in this study, it is not used, as for the best of our knowledge.

The use of wood, paper-based and textile materials as a substrate for RFID tags is quite a new approach. In addition, because of the wide variety of different paper- and wood-based materials together with the almost unlimited amount of different textile materials there is still much work to be done in finding the electrical characteristics of these materials [Vir12]. In this study, new substrate materials for UHF RFID have been studied, including cardboard, plywood and textile. In future one very interesting new substrate material could be biodegradable polymers. In this material field there are plenty of choices, and even more is now under intense development work. Some of the biodegradable polymers can be used in medical applications, even implanted inside a human body, and some are targeted for instance to bio waste bags [Dop13, Moh00]. In the era of the IoT all these kinds of items need to be identified, and the need for sensors with these kinds of materials is certainly a topic in the future.

REFERENCES

[Aha15] Ahamed, M., Akhtar, M. J., Alhadlaq, H. A., Alrokayan, S. A., “Assesment of the lung toxicity of copper oxide nanoparticles: current status”, Nanomedicine, Vol. 10, No. 15, 2015, pp. 2365–2377.

[All08] Allen, M. L., Aronniemi, M., Mattila, T., Alastalo, A., Ojanperä, K., Suhonen, M., Seppä, H., ”Electrical sintering of nanoparticle structures”, Nanotechnology, Vol. 19, No. 17, 2008, 4 p.

[Ami12] Amin, Y., Chen, Q., Zheng, L. R., Tenhunen, H. “Design and Fabrication of Wideband Archimedean Spiral Antenna Based Ultra-Low Cost “Green” Modules for RFID Sensing and Wireless Applications”, Progress In Electromagnetics Research, Vol. 130, 2012, pp. 241–256.

[Ani15] Ani Cu-IJ70 Datasheet, http://www.appliednanotech.net/tech/conductive_ink_cu.php , Accessed on 10th of April 2016.

[Asc97] Aschenbrenner, R., Ostmann, A., Motulla, G., Zakel, E., Reichl, H., ”Flip Chip Attachment Using Anisotropic Conductive Adhesives and Electroless Nickel Bumps”, IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part C, Vol. 20, No. 2, 1997, pp. 95–100.

[Bab12] Babar, A. A., Björninen, T., Bhagavati, V. A., Sydänheimo, L., Kallio, P., Ukkonen, L., ”Small and Flexible Metal Mountable Passive UHF RFID Tag on High-Dielectric Polymer-Ceramic Composite Substrate”, IEEE Antennas and Wireless Propagation Letters, Vol. 11, 2012, pp. 1319–1322.

[Bal05] Balanis, C. A., Antenna Theory. 3rd Edition, John Wiley & Sons, Hoboken, NJ, USA, 2005, 1118 p.

[Bha09] Bhattacharyya, R., Floerkemeier, C., Sarma, S., “Towards Tag Antenna Based Sensing – An RFID Displacement Sensor”, Proceedings of the IEEE International Conference on RFID, Orlando, FL, USA, April 27th–28th, 2009, pp. 95–102.

[Bha10] Bhattacharyya, R., Floerkemeier, C., Sarma, S., “Low-Cost, Ubiquitous RFID-Tag-Antenna-Based Sensing”, Proceedings of the IEEE, Vol. 98, No. 9, 2010, pp. 1593–1600.

[Bjö09] Björninen, T., Merilampi, S., Ukkonen, L., Sydänheimo, L., Ruuskanen, P., ”The Effect of Fabrication Method on Passive UHF RFID Tag Performance”, International Journal of Antennas and Propagation, Vol. 2009, 2009, 8 p.

[Bjö12] Björninen, T., Babar, A. A., Ukkonen, L., Sydänheimo, L., Elsherbeni, A. Z., Kallioinen, J., ”Compact Metal Mountable UHF RFID Tag on a Barium Titanate Based Substrate”, Progress In Electromagnetic Research C, Vol. 26, 2012, pp. 43–57.

[Bjö15a] Björninen, T., Virkki, J., Sydänheimo, L., Ukkonen, L., ”Manufacturing of antennas for passive UHF RFID Tags by direct write dispensing of copper and silver inks on textiles”, Proceedings of the International Conference on Electromagnetics in Advanced Applications (ICEAA), Turin, Italy, September 7th–11th, 2015, pp. 589–592.

[Bjö15b] Björninen, T., Virkki, J., Sydänheimo, L., Ukkonen, L., ”Possibilities of 3D Direct Write Dispensing for Textile UHF RFID Tag Manufacturing”, Proceedings of the IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, Canada, July 19th–24th, 2015, pp. 1316–1317.

[Bla05] Blayo, A. Pineaux, B., “Printing Processes and their Potential for RFID Printing”, Proceedings of the 2005 joint conference on Smart objects and ambient intelligence: innovative context-aware services: usages and technologies (sOc-EUSAI), Grenoble, France, October 12th–14th, 2005, pp. 27–30.

[Bro15] Broz, I., Bako, N., Butkovic, Z., Baric, A., “RFID UHF Protocol Implementation in Distributed Sensor Networks”, Proceedings of the 38th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, Croatia, May 25th–29th, 2015, pp. 68–73.

[Cat13] Catarinucci, L., Colella, R., De Donno, D., Tarricone, L., “Fully-Passive Devices for RFID Smart Sensing”, Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI), Orlando, FL, USA, July 7th–13th, 2013, pp. 2311–2312.

[Cha02] Chan, Y. C., Luk, D. Y., “Effects of bonding parameters on the reliability performance of anisotropic conductive adhesive interconnects for flip-chip-on-flex packages assembly II. Different bonding pressure”, Microelectronics Reliability, Vol. 42, No. 8, 2002, pp. 1195–1204.

[Cha07a] Chang, K., Kim, Y. H., Yoon, Y. J., “Functional antenna integrated with relative humidity sensor using synthesised polyimide for passive RFID sensing”, Electronics Letters, Vol. 43, No. 5, 2007, 2 p.

[Cha07b] Chawla, V., Ha, D. S., “An overview of passive RFID”, IEEE Communications Magazine, Vol. 45, No. 9, 2007, pp. 11–17.

[Das10] Das, A., Digital Communication, Principles and System Modelling, Springer-Verlag, 2010, 246 p.

[Dea10] Deavours, D., Dobkin, D., "UHF Passive RFID Tag Antennas", in book: Guha, D., Antar, M. M., (ed.), Microstrip and Printed Antennas: New Trends, Techniques, and Applications, John Wiley & Sons Ltd, Chichester, UK, 2010, pp. 263–303.

[Dei13] Deivasigamani, A., Daliri, A., Wang, C. H., John, S., "A Review of Passive Wireless Sensors for Structural Health Monitoring", Modern Applied Science, Vol. 7, No. 2, 2013, pp. 57–76.

[Den11] Denneulin, A., Bras, J., Blayo, A., Neuman, C., " Substrate pre-treatment of flexible material for printed electronics with carbon nanotube based ink", Applied Surface Science, Vol. 257, No. 8, 2011, pp. 3645–3651.

[Den14] Deng, F., He, Y., Zhang, C., Feng, W., "ACMOS Humidity Sensor for Passive RFID Sensing Applications", Sensors, Vol. 14, No. 5, 2014, pp. 8728–8739.

[Der07] Cerbek, V., Steger, C., Weiss, R., Preishuber-Pflügl, J., Pistauer, M., "A UHF measurement and evaluation test system", Elektrotechnik & Informationstechnik, Vol. 124, No. 11, 2007, pp. 384–390.

[Dha13] Dharmadasa, R., Jha, M., Amos, D. A., Druffel, T. "Roon Temperature Synthesis of a Copper Ink for the Intense Pulsed Light Sintering of Conductive Copper Films", ACS Applied Materials & Interfaces, Vol. 5, No. 24, 2013, pp. 13227–13234.

[Dob05] Dobkin, D. M., Weigand, S. M., "Environmental Effects on RFID Tag Antennas", Proceedings of the IEEE MTT-S International Microwave Symposium, Long Beach, CA, USA, June 12th–17th, 2005, pp. 135–138.

[Dob08] Dobkin, D. M., The RF in RFID, Newnes, Burlington, USA, 2008, 504 p.

[Dop13] Doppalapudi, S., Jain, A., Khan, W., Domb, A., "Biodegradable polymers – an overview", Polymers for Advanced Technologies, Vol. 25, No. 5, 2013, pp. 427–435.

[Dra15] Drahi, E., Blayac, S., Borbely, A., Benabe, P., "Impact of ink synthesis on processing of inkjet-printed silicon nanoparticle thin films: A comparison of Rapid Thermal Annealing and photonic sintering", Thin Solid Films, Vol. 571, 2015, pp. 169–176.

[Fal11] Falat, T., Felba, J., Platek, B., Piasecki, T., Moscicki, A., Smolarek, A., "Low-temperature, photonic approach to sintering the ink-jet printed conductive microstructures containing nano sized silver particles", Proceedings of the 18th European Conference on Microelectronics and Packaging (EMPC), Brighton, UK, September 12th–15th, 2011, 4 p.

[Fal12] Falat, T., Platek, B., Felba, J., Moscicki, A., Smolarek, A., Stojek, K., "Photonic Sintering Process of Ink-Jet Printed Conductive

Microstructures", Proceedings of the 4th Electronic System-Integration Technology Conference (ESTC), Amsterdam, Netherlands, September 17th–20th, 2012, 5 p.

[Fen11] Fennani, B., Hamam, H., Dahmane, A. O., "RFID overview", Proceedings of the International Conference on Microelectronics (ICM), Hammamet, Tunisia, December 19th–22nd, 2011, 5 p.

[Fer15] Fernández-Salmerón, J., Rivadeneyra, A., Mertínez-Martí, F., Capitán-Vallvey, L. F., Palma, A. J., Carvajal, M. A., "Passive UHF RFID Tag with Multiple Sensing Capabilities", Sensors, Vol. 15, No. 10, 2015, pp. 26769–26782.

[Fer16] Ferdous, R. M., Reza, A. W., Siddiqui, M. F., "Renewable energy harvesting for wireless sensors using passive RFID tag technology: A review", Renewable and Sustainable Energy Reviews, Vol. 58, 2016, pp. 1114–1128.

[Fin03] Finkenzeller, K., RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification. 2nd Edition, John Wiley & Sons Ltd, Chichester, UK, 2003, 427 p.

[For95] Forsythe, J. S., George, G. A., Hill, D. J.T., O´Donnell, J. H., Pomery, P. J., Rasoul, F. A., "The Effect of Simulated Low Earth Orbit Radiation on Polyimides (UV Degradation Study)", Journal of Applied Polymer Science, Vol. 58, No. 10, 1995, pp. 1847–1856.

[Fuj] Dimatix Materials Printer DMP-2831 specifications. http://en.fujifilmamericas.com.uy/shared/bin/PDS00085-DMP2831.pdf, Accessed on 16th of February, 2016.

[Fuj10] Fujifilm Dimatix Materials Printer DMP-2800 Series User Manual, Fujifilm Dimatix, 2010, p. 158.

[Gia16] Gianesello, F., Bisognin, A., Titz, D., Luxey, C., Fernandez, C. A., Costa, J. R., Gloria, D., "3D Printing Technology: Enabling Innovative & Cost Effective Industrial Antenna Solution", International Conference on Antenna Technology (iWAT), Cocoa Beach, CA, USA, February 29th–March 2nd, 2016, pp. 55–56.

[Gli14] Gliga, A. R., Skoglung, S., Wallinder, I. O., Fadeel, B., Karlsson, H. L., "Size-dependent cytotoxicity of silver nanoparticles in human lung cells: the role of cellular uptake, agglomeration and Ag release", Particle and Fibre Toxicology, Vol. 11, No. 11, 2014, 17 p.

[Gu15] Gu, X., Yung, K.C., "Ink-jet printed high conductive silver traces on polymer substrates sintered at room temperature by a camera flash lamp", Proceedings of the 16th International Conference on Electronic Packaging Technology (ICEPT), Changsha, China, August 11th–14th, 2015, pp. 642–644.

[Hal11] Halonen, E., Pynttäri, V., Lilja, J., Sillanpää, H., Mäntysalo, M., Heikkinen, J., Mäkinen, R., Kaija, T., Salonen, P., ”Environmental protection of inkjet-printed Ag conductors”, Microelectronics Engineering, Vol. 88, No.9, 2011, pp. 2970–2976.

[Han11] Han, W.-S., Hong, J.-M., Kim, H.-S., Song, Y.-W., “Multi-pulsed white light sintering of printed Cu nanoinks”, Nanotechnology, Vol. 22, No. 39, 2011, 6 p.

[Har] Harima NPS-JL datasheet, https://www.harima.co.jp/en/products/electronics/pdf/brochure16e_23.pdf, Accessed on 10th of April, 2016.

[Haw10] Hawrylak, P. J., Mickle, M. H., “EPC Gen-2 Standard for RFID”, in book: Zhang, Y., Yang, L. T. Chen, J., RFID and Sensor Networks, Architectures, Protocols, Security, and Integrations, CRC Press, 2010, 626 p.

[Jia08] Jia, Y. Heiss, M., Fu, Q., Gay, N. A. ”A Prototype RFID Humidity Sensor for Built Environment Monitoring”, Proceedings of the International Workshop on Education Technology and Training & International Workshop on Geoscience and Remote Sensing (ETT and GRS), Shanghai, China, December 21st–22nd, 2008, pp. 496–499.

[Jok02] Jokinen, E., Ristolainen, E., ”Anisotropic conductive film flip chip joining using thin chips”, Microelectronics Reliability, Vol. 42, No. 12, 2002, pp. 1913–1920.

[Joo15] Joo, S.-J., Park, S.-H., Moon, C.-J., Kim, H.-S., ”A Highly Reliable Copper Nanowire/Nanoparticle Ink Pattern with High Conductivity on Flexible Substrate Prepared via a Flash Light-Sintering Technique”, Applied Materials and Interfaces, Vol. 7, No. 10, 2015, pp. 5674–5684.

[Jun15] Jung, Y. H., Chang, T.-H., Zhang, H., Yao, C., Zheng, Q., Yang, V. W., Mi, H., Kim, M., Cho, S. J., Park, D.-W., Jiang, H., Lee, J., Qui, Y., Zhou, W., Cai, Z., Gong, S., Ma, Z., “High-performance green flexible electronics based on biodegradable cellulose nanofibril paper”, Nature Communications, Vol. 6, Article no. 7170, 2015, 11 p.

[Kan05] Kang, S.-J. L., Sintering; Densification, Grain Growth, and Microstructure, Elsevier Ltd., UK, 2005, 265 p.

[Kan11] Kang, J. S., Ryu, J., Kim, H. S., Hahn, H. T., ”Sintering of Inkjet-Printed Silver Nanoparticles at Room Temperature Using Intense Pulsed Light”, Journal of Electronic Materials, Vol. 40, No. 11, 2011, pp. 2268–2277.

[Kan14] Kang, H., Sowade, E., Baumann, R. R., ”Direct Intense Pulsed Light Sintering of Inkjet-Printed Copper Oxide Layers within Six

Milliseconds", Applied Materials & Interfaces", Vol. 6, No. 3, 2014, pp. 1682–1687.

[Kar01] Karmhag, R., Niklasson, G. A., Nygren, M., "Oxidation kinetics of nickel nanoparticles", Journal of Applied Physics, Vol. 89, No. 5, 2001, pp. 3012–3017.

[Kel12] Kellomäki, T., Virkki, J., Merilampi, S., Ukkonen, L., "Towards Washable Wearable Antennas: a Comparison of Coating Materials for Screen-Printed Textile-Based UHF RFID Tags", International Journal of Antennas and Propagation, Vol. 2012. 11 p.

[Kha13] Khaleel, H. R., Hussain, M. A.-R., Abbosh, A. I. "Design, Fabrication, and Testing of Flexible Antennas", in book: Kishk, A. (ed.), Advancement in Microstrip Antennas with Recent Applications. InTech, Rijeka, Croatia, 2013, p. 383.

[Kha14] Khan, M. S., Islam, M. S., Deng, H. D., "Design of a Reconfigurable RFID Sensing Tag as a Generic Sensing Platform Toward the Future Internet of Things", IEEE Internet of Things Journal, Vol. 1, No. 4, 2014, pp. 300–310.

[Kha15] Khan, S., Lorenzelli, L., Dahiya, R. S. "Technologies for Printing Sensors and Electronics Over Large Flexible Substrates: A Review", IEEE Sensors Journal, Vol. 15, No. 6, 2015, pp. 3164–3185.

[Kim09a] Kim, H.-S., Dhage, S.R., Shim, D.-E., Hahn, H.T., "Intense pulsed light sintering of copper nanoink for printed electronics", Applied Physics A Materials Science & Processing, Vol. 97, No. 4, 2009, pp. 791–798.

[Kim09b] Kim, Y., Lee, B., Yang, S. Byun, I., Jeong, I., Cho, S. M., "Use of copper ink for fabricating conductive electrodes and RFID antenna tags by screen printing", Current Applied Physics, Vol. 12, No. 2, 2012, pp. 473–478.

[Kim11] Kim, I., Chun, S., "Effects of Solvent Type on Low-Temperature Sintering of Silver Oxide Paste to Form Electrically Conductive Silver Film", Journal of Electronic Materials, Vol. 40, No. 9, 2011, pp. 1977–1983.

[Kim14] Kim, J., Wang, Z., Kim, W. S., "Stretchable RFID for Wireless Strain Sensing With Silver Nano Ink", IEEE Sensors Journal, Vol. 14, No. 12, 2014, pp. 4395–4401.

[Kim15] Kim, S., Kawahara, Y., Georgiadis, A., Collado, A., Tenzeris, M. M., "Low-Cost Inkjet-Printed Fully Passive RFID Tags for Calibration-Free Capacitive/Haptic Sensor Applications", IEEE Sensors Journal, Vol. 15, No. 6, 2015, pp. 3135–3145.

[Kop15] Kopyt, P., Salski, B., Olszewska, M., Janczak, D., Sloma, M., Kurkus, T., Jakubowska, M., Gwarek, W., "Graphene-based Dipole Antenna for a UHF RFID Tag", Proceedings of the IEEE MTT-S International Microwave Symposium, Phoenix, AZ, USA, May 17th–22nd, 2015, 3 p.

[Kue13] Kuester, D., Popovic, Z., "How Good Is Your Tag?", IEEE Microwave Magazine, Vol. 14, No. 5, 2013, pp. 47–55.

[Kum11] Kumpulainen, T., Pekkanen, J., Valkama, J., Laakso, J., Tuokko, R., Mäntysalo, M., "Low temperature nanoparticle sintering with continuous wave and pulse lasers", Optics and Laser Technology, Vol. 43, No. 3, 2011, pp. 570–576.

[Lai96] Lai, S. L., Guo, J. Y., Petrova, V., Ramanath, G., Allen, L. H., "Size-Dependent Melting Properties of Small Tin Particles: Nanocalorimetric Measurements", Physical Review Letters, Vol. 77, No. 1, 1996, pp. 99–102.

[Lai15] Lai, Y.-L., Chang, L.-C., Lu, W.-C., "An RFID Aquarium Sensing System", Proceedings of the IEEE International Conference on Consumer Electronics (ICCE-TW), Taipei, Taiwan, June 6th–9th, 2015, pp. 272–273.

[Le12] Le, T., Thai, T. Lakafosis, V., Tenzeris, M., Lin, Z., Fang, Y., Sandhage, K., Wong, C., "Graphene Enhanced Wireless Sensors", Proceedings of the IEEE Sensors Conference, Taipei, Taiwan, October 28th–31st, 2012, 4 p.

[Lee11a] Lee, J.-S., Kim, J.-K., Kim, M.-S., Kang, N., Lee, J.-H., "Reliability of flip-chip bonded RFID die using anisotropic conductive paste hybrid material", Transactions of Nonferrous Metals Society of China, Vol. 21, Supplement 1, 2011, pp. 175–181.

[Lee11b] Lee, D. J., Park, S. H., Jang, S., Kim, H. S., Oh, J. H., Song, Y. W., "Pulsed light sintering characteristics of inkjet-printed nanosilver films on a polymer substrate", Journal of Micromechanics and Microengineering, Vol. 21, No. 12, 2011, 7 p.

[Lee14] Lee, J., Lee, B., Jeong, S., Kim, Y., "Microstructure and electrical property of laser-sintered Cu complex ink", Applied Surface Science, Vol. 307, No. 15, 2014, pp. 42–45.

[Li15] Li, W., Van den Bulcke, J., De Windt, I., Dhaene, J., Van Acker, J., "Moisture behaviour and structural changes of plywood during outdoor exposure", European Journal of Wood and Wood Products, Vol. 74, No. 2, 2015, pp. 211–221.

[Lim13] Lim, S., Joyce, M., Fleming, P. D., Aijazi, A. T., "Inkjet Printing and Sintering of Nano-Copper Ink", Journal of Science and Technology, Vol. 57, No. 5, 2013, pp. 50506-1 – 50506-7.

[Liu01] Liu, J., "ACA bonding technology for low cost electronics packaging applications – current status and remaining challenges", Soldering & Surface Mount Technology, Vol. 13, No. 3, 2001, pp. 39–57.

[Liu07] Liu, J., Lu, X.-Z., Cao, L.-Q., "Reliability aspects of electronics packaging technology using anisotropic conductive adhesives", Journal of Shanghai University, Vol. 11, No. 1, 2007, pp. 1–16.

[Lon15] Long, F., Zhang, X. D., Björninen, T., Virkki, J., Sydänheimo, L., Chan, Y.-C., Ukkonen, L., "Implementation and Wireless Readout of Passive UHF RFID Strain Sensor Tags based on Electro-Textile Antennas", Proceedings of the 9th European Conference on Antennas and Propagation (euCAP), Lisbon, Portugal, April 12th–17th, 2015, 5 p.

[Mar10] Marrocco, G., "Pervasive Electromagnetics: Sensing Paradigms by Passive RFID Technology", IEEE Wireless Communications, Vol. 17, No. 6, 2010, pp. 10–17.

[Mer10] Merilampi, S. L., Björninen, T., Vuorimäki, A., Ukkonen, L., Ruuskanen, P., Sydänheimo, L., "The Effect of Conductive Ink Layer Thickness on the Functioning of Printed UHF RFID Antennas", Proceedings of the IEEE, Vol. 98, No. 9, 2010, pp. 1610–1619.

[Moh00] Mohanty, A. K., Misra, M., Hinrichsen, G., "Biofibres, biodegradable polymers and biocomposites: An overview", Micromolecular Materials and Engineering, Vol. 246–277, No. 1, 2000, pp. 1–24.

[Mon99] Montoro, T., Manrique, E., Gonzáles-Reviriego, A., "Measurement of the refracting index of wood for microwave radiation", Holz als Roh- und Werkstoff, Vol. 57, No. 4, 1999, pp. 295–299.

[Mor10] Mortimer, M., Kasemets, K., Kahru, A., "Toxicity of ZnO and CuO nanoparticles to ciliated protozoa *Tetrahymena thermophile*", Toxicology, Vol. 269, No. 2–3, 2010, pp. 182–189.

[Män09] Mäntysalo, M., Pekkanen, V., Kaija, K., Niittynen, J., Koskinen, S., Halonen, E., Mansikkamäki, P., Hämeenoja, O., "Capability of Inkjet Technology in Electronics Manufacturing", Proceedings of the 59th Conference on Electronic Components and Technology, San Diego, CA, USA, May 26th–29th, 2009, pp. 1330–1336.

[Nii14] Niittynen, J., Abbel, R., Mäntysalo, M., Perelaer, J., Schubert, U. S., Lupo, D., "Alternative sintering methods compared to conventional thermal sintering for inkjet printed silver nanoparticle ink", Thin Solid Films, Vol. 556, 2014, pp. 452–459.

[Nik07] Nikitin, P. V., Rao, K. V. S., Lazar, S., "An Overview of Near Field UHF RFID", Proceedings of the IEEE International Conference on RFID, Grapevine, TX, USA, March 26th–28th, 2007, pp. 167–174.

[Nor15] Norita, S., Kumaki, D., Kobayashi, Y., Sato, T., Fukuda, K., Tokito, S., "Inkjet-printed copper electrodes using photonic sintering and their application to organic thin-film transistors", Organic Electronics, Vol. 25, 2015, pp. 131–134.

[Nov] Novacentrix Metalon HPS-021LV datasheet, http://store.novacentrix.com/v/vspfiles/assets/images/Metalon%20HPS-021LV_3340%202b2.pdf, Accessed on 10th of April, 2016.

[Nov11] Novacentrix Metalon ICI-021 datasheet, http://www.novacentrix.com/sites/default/files/pdf/Metalon%20ICI-021%202229_1.pdf, Accessed on 10th of April, 2016.

[nSc] nScrypt 3Dn series datasheet. http://nscrypt.com/wp-content/uploads/2015/08/nScrypt-3Dn-Brochure.pdf. Accessed on 31st of March, 2016.

[nSc12] nScrypt nSoft User's Guide, Machine Tool Generation 3 (MT Gen3). 2012. 94 p.

[NXP14] NXP UCODE G2iL and G2iL+ datasheet, SL3S1203_1213, 2014. 37 p.

[Ore11] Orecchini, G., Alimenti, F., Palazzari, V., Rida, A., Tenzeris, M. M., Roselli, L., "Design and fabrication of ultralow cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology", IET Microwaves, Antennas & Propagation, Vol. 5, No. 8, 2011, pp. 993–1001.

[Opd12] Opdahl, P. J., "Anisotropic Conductive Adhesives", in book: Chen, J., Cranton, W., Fihn, M. (ed.), Handbook of Visual Display Technology, Springer, 2012, pp. 990–996.

[Par07] Park, B.K., Kim, D., Jeong, S., Moon, J., Kim, J.S., "Direct writing of copper conductive patterns by ink-jet printing", Thin Solid Films, Vol. 515, No. 19, 2007, pp. 7706–7711.

[Par13] Park, S.-H., Jang, S., Lee, D.-J., Oh, J., Kim, H.-S., "Two-step flash light sintering process for crack-free inkjet-printed Ag films", Journal of Micromechanics and Microengineering, Vol. 23, No. 1, 2013, 9 p.

[Par14a] Park, S.-H., Kim, H.-S., "Flash light sintering of nickel nanoparticles for printed electronics", Thin Solid Films, Vol. 550, 2014, pp. 575–581.

[Par14b] Park, S.-H., Ching, W.-H., Kim, H.-S., "Temperature changes of copper nanoparticle ink during flash light sintering", Journal of Materials Processing Technology, Vol. 214, No. 11, 2014, pp. 2730–2738.

[Par15] Park, J., Nguyen, H. A. D., Park, S., Lee, J., Kim, B., "Roll-to-roll gravure printed silver patterns to guarantee printability and functionality for mass production", Current Applied Physics, Vol. 15, No. 3, 2015, pp. 367–376.

[Per09] Perelaer, J., Klokkenburg, M., Hendriks, C. E., Schubert, U. S., "Microwave Flash Sintering of Inkjet-Printed Silver Tracks on Polymer Substrates", Advanced Materials, Vol. 21, No. 47, 2009, pp. 4830–4834.

[Per12] Perelaer, J., Abbel, R., Wünscher, S., Jani, R., van Lammeren, T., Schubert, U. S., "Roll-to-Roll Compatible Sintering of Inkjet Printed Features by Photonic and Microwave Exposure: From Non-Conductive Ink to 40% Bulk Silver Conductivity in Less Than 15 seconds", Advanced Materials, Vol. 24, No. 19, 2012, pp. 2620–2625.

[Pol11] Polzinger, B., Schoen, F., Matic, V., Keck, J., Willeck, H., Eberhardt, W., Kueck, H., "UV-Sintering of Inkjet-Printed Conductive Silver Tracks", Proceedings of the 11th International Conference on Nanotechnology, Portland, Oregon, USA, August 15th–18th, 2011, pp. 201–204.

[Pol16] Polino, G., Abbel, R., Shanmugan, S., Bex, G. J. P., Hendrix, R., Brunetti, F., Di Carlo, A., Addriessen, R., Galagan, Y., "A benchmark study of commercially available copper nanoparticle inks for application in organic electronic devices", Organic Electronics, Vol. 34, 2016, pp. 130–138.

[Ram15] Ramirez, R. A., Rojas-Nastrucci, E. A., Weller, T. M., "3D Tag with Improved Read Range for UHF RFID Applications using Additive Manufacturing", Proceedings of the 16th Annual IEEE Wireless and Microwave Technology Conference (WAMICON), Cocoa Beach, FL, USA, April 13th–15th, 2015, 4 p.

[Ran91] Ranta, E., Tiilikainen, M., Lukion taulukot, WSOY, Porvoo, Finland, 1991, 126 p.

[Rao05] Rao, K. V. S., Nikitin, P. V., Lam, S. F., "Impedance Matching Concepts in RFID Transponder Design", Proceedings of the 4th IEEE Workshop on Automatic Identification Advanced Technologies (AutoID'05), Buffalo, NY, USA, October 17th–18th, 2005, pp. 39–42.

[Ren14] Ren, Y., Virkki, J., Sydänheimo, L., Ukkonen, L., "Optimization of manufacturing parameters for inkjet-printed and photonically sintered metallic nanoparticle UHF RFID tags", Electronics Letters, Vol. 50, No. 21, 2014, pp. 1504–1505.

[Ric10] Ricci, A., Facen, A., Grisanti, M., Boni, A., De Munari, I., Ciampolini, P., Morandi, C., "Low-Power Transponders for RFID", in book: Zhang, Y., Yang, L. T., Chen, J. (ed.), RFID and Sensor Networks. CRC Press, FL, USA, 2010, 626 p.

[Rid09] Rida, A., Yang, L., Vyas, R., Tenzeris, M. M., "Conductive Inkjet-Printed Antennas on Flexible Low-Cost Paper-Based Substrates for RFID and WSN Applications", IEEE Antennas and Propagation Magazine, Vol. 51, No. 3, 2009, pp. 13–23.

[Rid10] Rida, A., Yang, L., Tenzeris, M., RFID-Enabled Sensor Design and Applications, Artech House, MA, USA, 2010, 212 p.

[Rud11] Rudander, J. H., Khuda, I.-E., Kildal, P.-S., Orlenius, C., "Measurements of RFID Tag Sensitivity in Reverberation Chamber", IEEE Antennas and Wireless Propagation Letters, Vol. 10, 2011, pp. 1345–1348.

[Ryu11] Ryu, J., Kim, H.-S., Hahn, T., "Reactive Sintering of Copper Nanoparticles Using Intense Pulsed Light for Printed Electronics", Journal of Electronic Materials, Vol. 40, No, 1, 2011, pp. 42–50.

[Sag14] Saghlatoon, H., Sydänheimo, L., Ukkonen, L., Tentzeris, M., "Optimization of Inkjet Printing of Patch Antennas on Low-Cost Fibrous Substrates", IEEE Antennas and Wireless Propagation Letters, Vol. 13, 2014, pp. 915–918.

[Saj15] Sajid, M., Ilyas, M., Basheer, C., Tariq, M., Daud, M., Baig, N., Shehzad, F., "Impact of nanoparticles on human and environment: review of toxicity factors, exposures, control strategies, and future prospects", Vol. 22, No. 6, 2015, pp. 4122–4143.

[Sam08] Sample, A. P., Yeager, D. J., Powledge, P. S., Mamishev, A. V., Smith, J. R., "Design of an RFID-Based Battery-Free Programmable Sensing Platform", IEEE Transactions on Instrumentation and Measurement, Vol. 57, No. 11, 2008, pp. 2608–2615.

[San15] Sanchez-Romaguera, V., Wünscher, S., Turki, B. M., Abbel, R., Barbosa, S., Tate, D. J., Oyeka, D., Batchelor, J. C., Parker, E. A., Schubert, U. S., Yeates, S. G., "Inkjet printed paper based frequency selective surfaces and skin mounted RFID tags: the irrelation between silver nanoparticle ink, paper substrate and low temperature sintering technique", Journal of Materials Chemistry C, Vol. 3, 2015, pp. 2132–2140.

[Sar02] Sarma, S. E., Weis, S. A., Engels, D. W. "RFID Systems and Security and Privacy Implications" in book: Kaliski, B. S., Koç, ç. K., Paar, C. (Ed.), Cryptographic Hardware and Embedded Systems - CHES 2002, Springer-Verlag, Germany, 2002, pp. 454–469.

[Sch06] Schroder, K. A., McCool, S. C., Furlan, W. F., "Broadcast Photonic Curing of Metallic Nanoparticle Films", Proceedings of the NSTI Nanotechnology Conference and Trade Show, Boston, USA, May 7th–11th, Vol. 3, 2006, pp. 198–201.

[She15] Shemelya, C. M., Zemba, M., Liang, M., Espalin, D., Kief, C. Xin, H., Wicker, R. B., MacDonald, E. W., “3D Printing Multifunctionality: Embedded RF Antennas and Components”, Proceedings of the 9th European Conference on Antennas and Propagation (euCAP), Lisbon, Portugal, April 12th–17th, 2015, 5 p.

[Shi13] Shin, K.-Y., Lee, M., Kang, H., Kang, K., Hwang, J. Y., Kim, J.-M., Lee, S.-H., ”Characterization of Inkjet-Printed Silver Pattern for Application to Printed Circuit Board (PCB)”, Journal of Electrical Engineering & Technology, Vol. 8, No. 3, 2013, pp. 603–609.

[Smi05] Smith, J. R., Fishkin, P., Jiang, B., Mamishev, A., Philipose, M. Rea, A. D., Roy, S., Sundara-Rajan, K., “RFID-Based Techniques for Human-Activity Detection”, Communications of the ACM, Vol. 48, No. 9, 2005, pp. 39–44.

[Sto48] Stockman, H., “Communication by Means of Reflected Power”, Proceedings of the Institute of Radio Engineers, Inc., Vol. 36, 1948, pp. 1196–1204.

[Sug14] Suganuma, K., Introduction to Printed Electronics, Springer, 2014, 129 p.

[Tek08] Tekin, E., Smith, P. J., Schubert, U. S., “Inkjet printing as a deposition and patterning tool for polymers and inorganic particles”, Soft Matter, No. 4, 2008, pp. 703–713.

[Tob11] Tobjörk, D., Österbacka, R., “Paper Electronics”, Advanced Materials, Vol. 23, No. 17, 2011, pp- 1935–1961.

[Udd03] Uddin, M. A., Alam, M. O., Chan, Y. C., Chan, H. P., “Adhesion strength and contact resistance of flip chip on flex packages – effect of curing degree of anisotropic conductive film”, Microelectronics Reliability, Vol. 44, No. 3, 2004, pp. 505–514.

[Vae13] Vaezi, M., Seitz, H., Yang, A., ”A review on 3D micro-additive manufacturing technologies”, The International Journal of Advanced Manufacturing Technology, Vol. 67, No. 5, 2013, pp. 1721–1754.

[Vir11] Virtanen, J., Ukkonen, L., Björninen, T., Elsherbeni, A. Z., Sydänheimo, L., ”Inkjet-Printed Humidity Sensor for Passive UHF RFID Systems”, IEEE Transactions on Instrumentation and Measurement, Vol. 60, No. 8, 2011, pp. 2768–2777.

[Vir12] Virtanen, J., Virkki, J., Ukkonen, L., Sydänheimo, L., ”Inkjet-Printed UHF RFID Tags on Renewable Materials”, Advances in Internet of Things, Vol. 2, No. 4, 2012, pp. 79–85.

[Vir13a] Virtanen, J., Virkki, J., Sydänheimo, L., Tenzeris, M., Ukkonen, L., ”Automated Identification of Plywood Using Embedded Inkjet-Printed

Passive UHF RFID Tags", IEEE Transactions on Automation Science and Engineering, Vol. 10, No. 3, 2013, pp. 796–806.

[Vir13b] Virkki, J., Björninen, T., Merilampi, S., Sydänheimo, L., Ukkonen, L., "Manufacturing and Applications of Screen-printed RFID Tags on Paper Substrate", Proceedings of the Progress in Electromagnetics Research Symposium (PIERS), Stockholm, Sweden, August 12th–15th, 2013, pp. 562–566.

[Vir14a] Virkki, J., Björninen, T., Sydänheimo, L., Ukkonen, L., "Brush-painted Silver Nanoparticle UHF RFID Tags on Fabric Substrates", Proceedings of the Progress in electromagnetics research symposium (PIERS), August 25th–28th, Guangzhou, China, 2014, pp. 2106–2110.

[Vir14b] Virkki, J., Björninen, T., Kellomäki, T., Merilampi, S., Shafiq, I., Ukkonen, L., Sydänheimo, L., Chan, Y.C., "Reliability of washable wearable screen printed UHF RFID tags", Microelectronics Reliability, Vol. 54, No. 4, 2014, pp. 840–846.

[Vol11] Volkman, S. K., Yin, S., Bakhishev, T., Puntambekar, K., Subramanian, V., "Mechanistic Studies on Sintering of Silver Nanoparticles", Chemistry of Materials, Vol. 23, No. 10, 2011, pp. 4634–4640.

[Vya09] Vyas, R., Lakafosis, V., Rida, A., Chaisilwattana, N., Travis, S., Pan, J., Tenzeris, M. M., "Paper-Based RFID-Enabled Wireless Platforms for Sensing Applications", IEEE Transactions on Microwave Theory and Techniques, Vol. 57, No. 5, 2009, pp. 1370–1382.

[Wan04] Want, R. "Enabling Ubiquitous Sensing with RFID", Computer, Vol. 37, No. 4, 2004, pp. 84–86.

[Wan06] Want, R., "An Introduction to RFID technology", IEEE Pervasive Computing, Vol. 5, No. 1, 2006, pp. 25–33.

[Wan13] Wang, B.-Y., Yoo, T.-H., Song, Y.-W., Lim, D.-S., Oh, Y.-J., "Cu Ion ink for a Flexible Substrate and Highly Conductive Patterning by Intensive Pulsed Light Sintering", ACS Applied Materials & Interfaces, Vol. 5, No. 10, 2013, pp. 4113–4119.

[Wen05] Wentworth, S. M., Fundamentals of Electromagnetics with Engineering Applications, John Wiley & Sons Inc., Hoboken, NJ, USA, 2005, 590 p.

[Wes12] West, J., Carter, M. Smith, S., Sears, J., "Photonic Sintering of Silver Nanoparticles: Comparison of Experiment and Theory" in book: Shatokha, V. (Ed.), Sintering–Methods and Products, InTech, 2012, p. 316.

[Xen13] Xenon Sinteron 2010-L., Installation and User Manual, Xenon Corporation, June 2013.

[Yam96] Yamamatsu, J., Kawano, N., Arashi, T., Sato, A., Nakano, Y., Nomura, T., ”Reliability of multilayer ceramic capacitors with nickel electrodes”, Journal of Power Sources, Vol. 60, No. 2, 1996, pp. 199–203.

[Yea10] Yeager, D., Zhang, F., Zarrasvand, A., Otis, B. P., “A 9.2µA Gen 2 Compatible UHF RFID Sensing tag with -12dBm Sensitivity and 1.25µV_{rms} Input-Referred noise Floor”, Proceedings of the IEEE International Solid-State Circuits Conference, San Francisco, CA, USA, February 7th–11th, 2010, pp. 52–53.

[Zen14] Zenou, M., Ermak, O., Saar, A., Kotler, Z., “Laser sintering of copper nanoparticles”, Journal of Physics D: Applied Physics, Vol. 47, No. 2, 2014, 11 p.

[Zhe07] Zheng, S., Yu, F., Zhu, Y., “A Novel RFID Transceiver Architecture with Enhanced Readability”, Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing, Shanghai, China, September 21st–25th, 2007, pp. 2074–2077.

PUBLICATION I

Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2016, Article ID 3694198, 8 pages
http://dx.doi.org/10.1155/2016/3694198

Research Article

Brush-Painting and Photonic Sintering of Copper Oxide and Silver Inks on Wood and Cardboard Substrates to Form Antennas for UHF RFID Tags

Erja Sipilä,[1] Johanna Virkki,[1] Jianhua Wang,[2] Lauri Sydänheimo,[1] and Leena Ukkonen[1]

[1]*Department of Electronics and Communications Engineering, Tampere University of Technology, P.O. Box 692, 33101 Tampere, Finland*
[2]*Faculty of Automation, Guangdong University of Technology, No. 100 Waihuan Xi Road, Guangzhou Higher Education Mega Center, Panyu District, Guangzhou 510006, China*

Correspondence should be addressed to Erja Sipilä; erja.sipila@tut.fi

Received 26 January 2016; Accepted 28 April 2016

Academic Editor: Miguel Ferrando Bataller

Additive deposition of inks with metallic inclusions provides compelling means to embed electronics into versatile structures. The need to integrate electronics into environmentally friendly components and structures increases dramatically together with the increasing popularity of the Internet of Things. We demonstrate a novel brush-painting method for depositing copper oxide and silver inks directly on wood and cardboard substrates and discuss the optimization of the photonic sintering process parameters for both materials. The optimized parameters were utilized to manufacture passive ultra high frequency (UHF) radio frequency identification (RFID) tag antennas. The results from wireless testing show that the RFID tags based on the copper oxide and silver ink antennas on wood substrate are readable from ranges of 8.5 and 11 meters, respectively, and on cardboard substrate from read ranges of 8.5 and 12 meters, respectively. These results are well sufficient for many future wireless applications requiring remote identification with RFID.

1. Introduction

Material choices in future wireless components and devices will have a huge effect on the environment and consequently the use of biodegradable, environment-friendly substrate materials, for example, cardboard, wood, textile, and paper, has been an increasing trend in electronics during the recent years [1–5]. In addition, the concept of embedding electronics as a part of versatile structures offers potential for novel applications and many industries are interested in these smart products. For example, cardboard is anindispensable material in the packaging and graphics industry, which also makes it an interesting substrate material for electronics, especially considering low cost electronics [6]. Great possibilities also lie in the construction industry, where wood is a typical material, as well as in the plywood industry itself [7, 8].

Excessive potential for future environmentally friendly wireless applications can be found from passive ultra high frequency (UHF) radio frequency identification (RFID) technology. Passive UHF RFID technology provides a method for automatic identification and tracking of items with battery-free remotely addressable electronic tags composed of an antenna and an integrated circuit (IC). The use of propagating electromagnetic waves in the UHF regime for powering and communicating with the passive tags enables rapid interrogation of a large quantity of tags through various media [9]. In comparison to barcodes, IC-enabled RFID tags allow the data stored in them to be updated wirelessly at any time. Thanks to the energy efficient mechanism of digitally modulated scattering utilized in the tag-to-reader wireless communication, the data can be read from a distance of several meters. This makes passive UHF RFID tags an interesting technology to be used as "proof of concept" for future environmentally friendly electronics [10, 11]. For further information on RFID technology, a survey of the history of RFID is presented in [12] and an introduction to today's systems, especially to

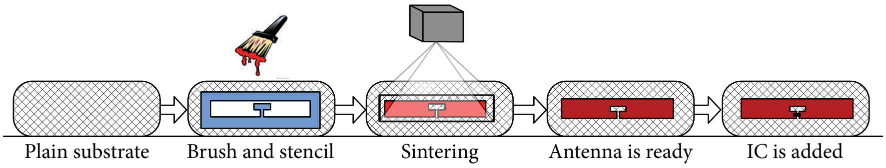


FIGURE 1: Brush-painting process.

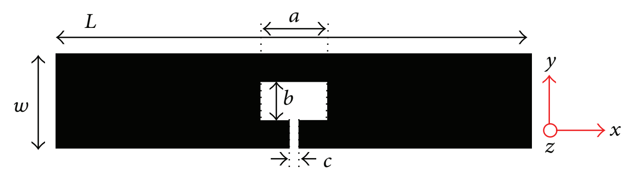
passive UHF RFID technology used in this study, is provided in [13, 14]. Finally, a thorough introduction of the design of antennas for RFID tags can be found in [15, 16].

In this study, the optimal photonic sintering parameters for brush-painted copper oxide and silver ink antennas on wood and cardboard substrates were studied. These sintering parameters were then used to manufacture environmentally friendly passive UHF RFID tag antennas. The work presented here is organized as follows. After Introduction, Section 2 introduces our tag design and the used brush-painting and sintering methods. Section 3 presents the actual tag fabrication with the optimized manufacturing parameters. The wireless tag measurements are introduced in Section 4. Section 5 presents the results and Section 6 summarizes the conclusions of this study.

2. Brush-Painting and Photonic Sintering of Antennas

Brush-painting is a versatile but simple and fast additive manufacturing method that can be integrated into manufacturing process of products incorporated with RFID tags. The method not only reduces process steps but also minimizes the need of conductive material, as the material is dispensed directly to the brush and from the brush directly to the antenna area in the substrate. This reduces costs and is more environment-friendly, especially when compared to the widely used etching process in RFID manufacturing. The brush-painting process steps are presented in Figure 1. Brush-painting has been previously successfully used for fabrication of tag antennas on fabric substrate with silver nanoparticle ink [1] and on wood substrate with silver and copper nanoparticle inks [2]. In this study, screen printable silver and copper oxide inks were used. The RFID tag manufacturing process for nanoparticle inks in study [2] and screen printable inks in this study is exactly the same. The only difference is in the photonic sintering parameters; the sintering parameters have to be chosen for every ink and material combination independently.

Copper and silver tag antennas were brush-painted through a stencil (50 μm thick polyimide film) on wood and cardboard substrates, by using only one layer of ink. The wood substrate used in this study is 4 mm thick plywood with 3 wood layers and the cardboard is normal packaging cardboard. Wood and cardboard are lossy materials but due to the thin substrates they are not expected to affect the tag performance significantly. However, it can be assumed that the use environment, for example, varying moisture content, will influence the performance of RFID tags on



Geometrical parameters in millimeters				
L	W	a	b	c
100	20	14.3	8.125	2

FIGURE 2: Studied tag antenna geometry.

wood and cardboard, as the tag antenna impedance and the ohmic losses are affected by the surrounding materials [17]. The next step, when continuing in this study area, is to use simulation methods to study the effects of the substrate thickness variation and the effects of different environmental stresses on the tag performance.

A compact tag antenna shown in Figure 2 was utilized as the antenna geometry. The simple antenna geometry was chosen for the prototype manufacturing purpose; it is not optimized to be used on wood or cardboard substrate. The used silver ink was Metalon HPS-021LV silver flake ink [18] and the used copper ink was Metalon ICI-021 copper oxide ink [19].

Heat sintering in an oven is nowadays commonly used in additive manufacturing. However, the needed sintering times are long and usually the needed temperatures are high. Flash lamp sintering is a photonic sintering method that in ambient conditions uses short light pulses from a flash lamp to heat the ink to a high enough temperature within few milliseconds [2, 20]. Photonic sintering is advantageous in mass productions because of its extremely short process time together with the ability to be done in normal room conditions, which also allows the use of temperature sensitive substrate materials [21]. In addition to silver ink, photonic sintering also allows the use of more cost-effective copper ink, which cannot be sintered by heat sintering because of the insulating oxide formation during sintering process [22, 23]. In this study, the photonic sintering was done using Xenon Sinetron 2010-L system, which provides a high energy pulsed light for sintering of conductive particles. The sintering system parameters are lamp voltage, flash pulse duration, and number of flash pulses. The lamp voltage can be adjusted between 1800 V and 3000 V, in 50 V increments, and the pulse duration can be adjusted up to 2000 μs [24]. The energy of each flash pulse can be calculated using the following formula:

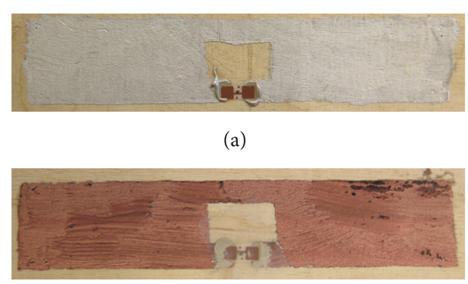
$$E = \left(\frac{V}{3120}\right)^{2.4} \cdot t, \tag{1}$$

Table 1: Sintering parameters and resistance measurements.

Sample number	Substrate material	Conductive ink	Sintering parameters	Number of flash pulses needed	Light energy from lamp [kJ]	Resistance [Ω]
1	Wood	Ag	1000 μs, 2800 V	3	2.314	1.1
2	Wood	Ag	2000 μs, 2200 V	2	1.729	0.6
3	Wood	Ag	2000 μs, 2500 V	2	2.350	0.5
4	Wood	Ag	2000 μs, 2800 V	1	1.543	0.5
5	Wood	Ag	2000 μs, 3000V	1	1.820	0.4
6	Wood	Cu	1500 μs, 2600 V	1	0.968	4.7
7	Wood	Cu	2000 μs, 2000 V	3	2.064	Not conducting
8	Wood	Cu	2000 μs, 2200 V	2	1.729	11.7
9	Wood	Cu	2000 μs, 2400 V	1	1.066	5.0
10	Cardboard	Ag	1000 μs, 2800 V	3	2.314	0.6
11	Cardboard	Ag	2000 μs, 2200 V	2	1.729	0.7
12	Cardboard	Ag	2000 μs, 2500 V	2	2.350	0.6
13	Cardboard	Ag	2000 μs, 2800 V	1	1.543	Not conducting
14	Cardboard	Cu	1500 μs, 2600 V	1	0.968	10.0
15	Cardboard	Cu	2000 μs, 2000 V	2	1.376	9.7
16	Cardboard	Cu	2000 μs, 2200 V	1	0.865	5.8
17	Cardboard	Cu	2000 μs, 2200 V	2	1.729	10.5
18	Cardboard	Cu	2000 μs, 2400 V	1	1.066	Not conducting

where E is the energy in Joules per pulse, V is the voltage in Volts, and t is the time in microseconds [24]. This is the energy that the lamp produces.

Despite the obvious advantages of photonic sintering, finding the optimized sintering parameters is the biggest challenge. Too high sintering voltage or too long pulse duration, in other words too high sintering energy, can directly damage the ink layer and the substrate [25], while too low sintering voltage and short time can lead to poor or partial sintering. In addition, the sintering parameters for each substrate and ink material need to be studied individually [25]. Incorrect placement of the tag antenna in the sintering device can also lead to poor sintering performance, either to partial sintering or to burned ink layer.



(a)

(b)

Figure 3: (a) Sample 4, a silver antenna on wood substrate, and (b) Sample 9, a copper antenna on wood substrate.

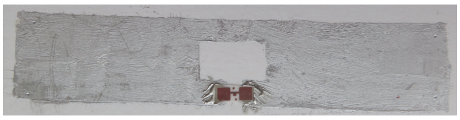
3. Fabrication of Passive UHF RFID Tags

The brush-painted antennas were sintered with Xenon Sinetron 2010-L system. In this study, the lamp voltage was changed from 2000 V to 3000 V. The used pulse widths in tests were 1000 μs, 1500 μs, and 2000 μs. Sintering was started with a single flash pulse. After sintering, a visual inspection together with preliminary resistance measurements was done and, based on these results, it was decided if sintering with two flash pulses should be tested. Similarly, the need for third flash pulse was decided after two flash pulses. If the results of visual inspection and resistance measurement were suitable already after one flash pulse, further flash pulses were not done, as the goal was to use as few flash pulses as possible. In addition, if it became clear after one flash pulse that the sintering energy was already too high, further sintering with more flash pulses was not done.

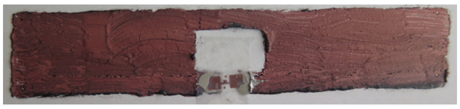
It was quickly discovered that 1000 μs and 1500 μs are too short pulse widths, which were not enough even after multiple flash pulses. Thus, we manufactured most of the samples using the maximum pulse width, 2000 μs.

The resistances of the sintered antennas were measured using a Fluke 115 multimeter. The measurement probes were placed in the opposite corners of the fabricated antenna. The measured resistances and the total flash light energy for antennas manufactured with different parameters can be seen in Table 1. The energy is calculated using (1). Based on the resistance measurements and visual inspection results, two best tag antennas from each of the 4 slots (copper/silver ink and cardboard/wood substrate) were chosen for wireless measurements. Figures 3 and 4 show sintered silver and copper antennas on wood and cardboard substrates, respectively.

All the tags fabricated with silver ink on wood substrate were found to show low resistances and very little variation



(a)



(b)

Figure 4: (a) Sample 10, a silver antenna on cardboard substrate, and (b) Sample 15, a copper antenna on cardboard substrate.

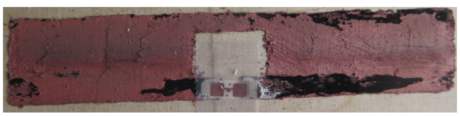


Figure 5: Burned areas on the antenna surface of Sample 6.

Figure 6: A close-up photo of partially sintered antenna in Sample 7.

Figure 7: A close-up photo of burned antenna in Sample 13.

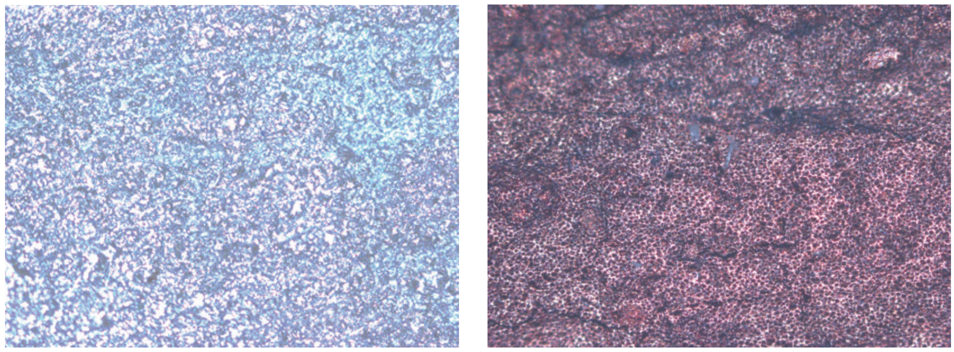
in resistance measurement results with different sintering parameters and different sintering energy (see Table 1). The highest resistance among silver ink antennas on wood substrate was 1.1 Ω, measured for Sample 1 (1000 μs, 2800 V, 3 flash pulses). However, also this result would be low enough for a working UHF RFID tag antenna. By using 1 or 2 flash pulses with the same parameters the antenna was not fully sintered and residues of the nonsintered ink were seen. These results indicate that 1000 μs is too short pulse width, especially as minimum number of flash pulses is desirable: the number of flash pulses has an effect on the process time and can be an essential factor in fast mass production of electronics. Sample 4 (2000 μs, 2800 V, 1 flash pulse) and Sample 5 (2000 μs, 3000 V, 1 flash pulse) were chosen to wireless measurements; they had the lowest resistance values, 0.5 Ω and 0.4 Ω, respectively, with a minimum number of flash pulses.

The copper oxide ink antennas on wood substrate had a larger variation in resistances than the silver ink counterparts. In general, the copper oxide ink antennas also had higher resistance values than silver ink antennas, which correspond to materials' general conductivities [18, 19]. Sample 6 (1500 μs, 2600 V, 1 flash pulse) and Sample 9 (2000 μs, 2400 V, 1 flash pulse) showed the lowest resistances, 4.7 Ω and 5.0 Ω, respectively, and they were chosen to further measurements. In addition to the lowest resistance values, they had the lowest total light energy but at the same time the highest light energy per one light pulse and higher sintering voltages than the other two samples in this test lot. Despite the lowest resistance measurement result, the surface of Sample 6 did not look as smooth as the surface of Sample 9: the surface of Sample 6 is partly oversintered and small burned areas can be seen on the surface (see Figure 5). This indicates that the sintering voltage has been little too high. Sample 7 (2000 μs, 2000 V, 3 flash pulses) was not conductive at all, meaning the sintering power was too low initially. Even after 3 flash pulses the sample surface looked undersintered (see Figure 6) and hence it shows that even though the total amount of energy after 3 flash pulses is high enough, the sintering voltage is too low for this material combination.

The silver ink was found to be easily sintered also on cardboard substrate. Again, very minor variations in resistances were found, except for Sample 13 (2000 μs, 2800 V, 1 flash pulse), which was not conductive at all. From Figure 7 it can be seen that the silver ink has burned away from parts of the cardboard substrate, meaning too high sintering energy per one flash pulse. Sample 13 had the highest light energy per one pulse (see Table 1) in this test lot with silver ink on card board substrate. Similar effect was seen in Sample 12 (2000 μs, 2500 V, 2 flash pulses) but the burning of the ink layer was not as bad as in Sample 13 and the resistance result was good, 0.6 Ω. The light energy per one flash pulse was lower with sample 12 than with sample 13. Samples 10 (1000 μs, 2800 V, 3 flash pulses) and 11 (2000 μs, 2200 V, 2 flash pulses) were chosen for further measurements; their resistance measurement results were 0.6 Ω and 0.7 Ω, respectively, even though marks of oversintering can also be seen in Sample 11.

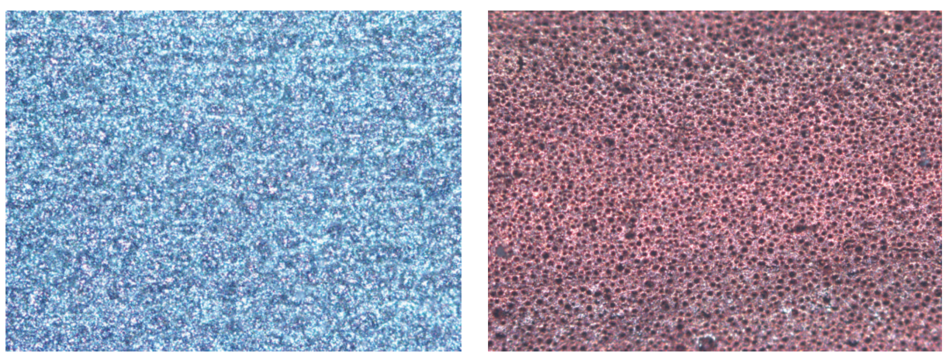
As with copper ink on wood substrate, large variations in resistance results were found with copper ink on cardboard substrate. Sample 15 (2000 μs, 2000 V, 2 flash pulses) and Sample 16 (2000 μs, 2200 V, 1 flash pulse) with resistances of 9.7 Ω and 5.8 Ω were chosen to further measurements. In Sample 14 (1500 μs, 2600 V, 1 flash pulse), Sample 17 (2000 μs, 2200 V, 2 flash pulses), and Sample 18 (2000 μs, 2400 V, 1 flash pulse) burned areas can be seen in visual inspection and this indicates that the sintering energy has been too high in these cases. Because of the results of visual inspection, further testing with 2 and 3 flash pulses was not done with these samples.

It has been found that if samples are overexposed to the xenon lamp, thus if too much energy is applied on the sample the sample is damaged and its electrical properties are decreased [26]. On the other hand if the light energy is



(a) (b)

Figure 8: Optical microscope images (magnification ×5) of sintered silver ((a) Sample 4) and copper ((b) Sample 8) ink layers on wood substrate.



(a) (b)

Figure 9: Optical microscope images (magnification ×5) of sintered silver ((a) Sample 10) and copper ((b) Sample 16) ink layers on cardboard substrate.

too low, the conductive ink pattern is not thoroughly sintered. The photonic sintering process goes from surface to deeper in the conductive ink layer [27]. If the sintering energy is too low, unsintered layers exist inside the antenna structure, causing performance degradation and total nonfunctioning, as seen, for example, with Sample 7.

Photonic sintering of the copper ink was found to be significantly more challenging than photonic sintering of the silver ink. The exact optimal parameters for copper oxide ink are much more significant for good conductivity than for silver ink and thus a wider range of sintering parameters can be used with silver ink than with copper oxide ink. This can also be seen in the results presented in Table 1. Optical microscope images of sintered silver and copper ink layers on wood and cardboard substrates can be seen in Figures 8 and 9, respectively.

The tag IC utilized in this experiment was NXP UCODE G2iL series IC [28], which has a low wake-up power of 15.8 μW (−18 dBm). The manufacturer had mounted the chip on a fixture with two $3 \times 3\,\text{mm}^2$ pads which we connected to the antenna terminals using conductive epoxy (Circuit Works CW2400). However, when considering the future possibilities in RFID tag manufacturing, flip chip technology together with anisotropic conductive adhesives could make the fabrication process of environmentally friendly tags even faster.

4. Wireless Testing of the Tags

The manufactured tags were measured using Voyantic Tagformance measurement system [29] to conduct the measurement through a range of frequencies from 800 MHz to 1000 MHz. The core operations are performed with a vector signal analyzer. Two key properties of passive UHF RFID tags, threshold power and theoretical read range, were measured as a function of transmit frequency.

Threshold power describes the minimum transmit power, at the transmit port, to activate the tag and can be expressed as

$$P_{TS} = \frac{P_{IC}}{G_{tx} G_{tag} \tau \left(\lambda / 4\pi d\right)^2 \left| p_{tx}^{\wedge} \cdot p_{tag}^{\wedge} \right|^2}, \tag{2}$$

where P_{IC} is the sensitivity of the RFID IC, G_{tx} and G_{tag} are the gains of the reader and tag antenna, τ is the power transmission coefficient, d is the distance between the tag and reader antenna, and p_{tx} and p_{tag} the unit electric field vectors of the transmitting antenna and tag antenna. The

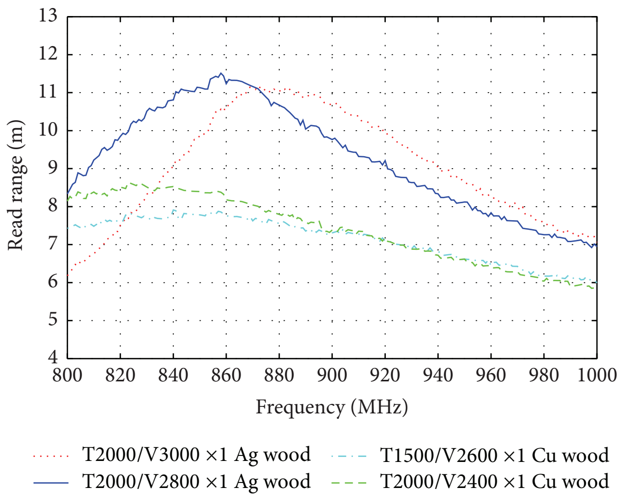


Figure 10: Attainable read ranges of copper and silver tags on wood substrates.

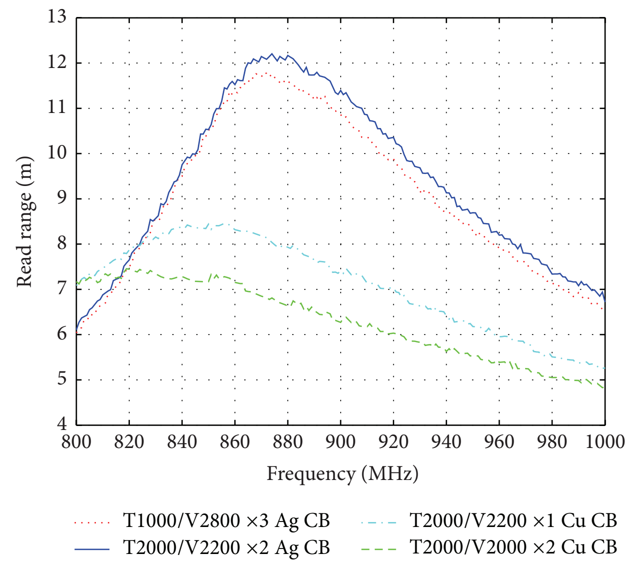


Figure 11: Attainable read ranges of copper and silver tags on cardboard substrates.

inner product of the electric field vectors describes the power loss due to possibly mismatched polarization planes between the reader and tag antenna.

Theoretical read range describes the maximal distance between the tag and reader antenna in an environment without reflections or external disturbances. The Tagformance measurement system is able to calculate the theoretical read range of a tag using its measured threshold power along with the measured forward losses. The forward loss describes the link loss between the generator's output port and the input port of an equivalent isotropic antenna placed at the tag's location. The forward loss from the transmit port to the tag is calculated using a reference tag during the calibration procedure of Tagformance. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels and can be calculated as

$$d_{\text{tag}} = \frac{\lambda}{4\pi}\sqrt{\frac{\text{EIRP}}{P_{\text{TS}}L_{\text{fwd}}}}, \quad (3)$$

where λ is the wavelength transmitted from the reader, EIRP is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, and P_{TS} and L_{fwd} are the measured threshold power and forward losses correspondingly.

5. Wireless Measurement Results

Figures 10 and 11 show the attainable read ranges for copper and silver tags on wood and cardboard substrates, respectively. It can be seen that the silver tags on both substrates perform very well. The attainable peak read ranges for silver tags on wood substrate are over 11 meters and for cardboard substrate over 12 meters. The read ranges through the global UHF RFID band are over 7 meters for silver tags on wood substrate and over 6.5 meters for the silver tags on cardboard substrates.

As expected, based on the resistance measurements, the copper tag read ranges are shorter than the silver tag read ranges. The attainable peak read ranges for copper tags on wood and cardboard substrates are over 8.5 meters. Through the global UHF RFID band the read ranges are over 6 meters and 5 meters for copper tags on wood and cardboard substrates, respectively.

The brush-painting of silver and copper nanoparticle inks on wood substrate has been reported in our previous study [2], where the same tag antenna geometry was brush-painted on wood and photonically sintered. The peak read ranges for tags with silver and copper nanoparticle ink antennas on wood substrate were about 5 meters and 3.5 meters, respectively [2]. In another study, inkjet-printed and heat-sintered silver nanoparticle tags on wood veneer with similar tag antenna geometry achieved peak read ranges of 6.5 meters and read ranges of over 2 meters throughout the global UHF RFID band [7]. In this study we achieved read ranges of over 11 meters with silver ink and over 8 meters with copper oxide ink on wood substrate by using screen printable inks.

These results indicate that the use of normal screen printable conductive ink is more beneficial than the use of nanoparticle conductive ink on wood substrate and that the brush-painted antennas offer an alternative to inkjet-printed and screen-printed antennas on biodegradable, environment-friendly substrates. It should be noted that the brush-painting method is not suitable for structures containing very small details; if very minor dimensions are required, inkjet printing is recommended. However, with basic geometries, it is possible to achieve RFID antennas with suitable read ranges by only one brushed layer. The read ranges of few meters are sufficient, for example, for identification purposes in the construction and packaging industry, and much longer read ranges would not give significant benefits to supply chain management or for identifying products during field use and after-sales services.

6. Conclusions

In this paper, we present a novel brush-painting method for depositing copper and silver conductive inks directly on wood and cardboard substrates. The method has a great potential to simplify manufacturing of wireless components. The optimal parameters for photonic sintering of copper oxide and silver inks on these substrates were studied and they were used to manufacture passive UHF RFID tag antennas. The manufactured copper and silver tags on wood substrate showed peak attainable read ranges of over 8.5 and 11 meters, respectively, and on cardboard substrate over 8.5 and 12 meters, respectively. Moreover, all of the tags exhibited read ranges of several meters throughout the whole global UHRF RFID band. These results offer a huge potential for applications in versatile industries requiring remote identification with RFID. Brush-painting with photonic sintering can be integrated into manufacturing process of RFID tags, which means the method has a great potential in manufacturing of environmentally friendly wireless components. In future, the authors will also study the possibilities of simulations with the manufacturing method presented in this study.

Competing Interests

None of the authors has any conflict of interests.

References

[1] J. Virkki, T. Björninen, L. Sydänheimo, and L. Ukkonen, "Brush-painted silver nanoparticle UHF RFID tags on fabric substrates," in *Proceedings of the Progress in Electromagnetics Research Symposium (PIERS '14)*, pp. 2106–2110, Guangzhou, China, August 2014.

[2] E. Sipila, J. Virkki, L. Sydanheimo, and L. Ukkonen, "Experimental study on brush-painted metallic nanoparticle UHF RFID tags on wood substrates," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 301–304, 2015.

[3] J. Virtanen, J. Virkki, A. Z. Elsherbeni, L. Sydänheimo, and L. Ukkonen, "A selective ink deposition method for the cost-performance optimization of inkjet-printed UHF RFID tag antennas," *International Journal of Antennas and Propagation*, vol. 2012, Article ID 801014, 9 pages, 2012.

[4] G. Orecchini, F. Alimenti, V. Palazzari, A. Rida, M. M. Tentzeris, and L. Roselli, "Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology," *IET Microwaves, Antennas & Propagation*, vol. 5, no. 8, pp. 993–1001, 2011.

[5] M. M. Tentzeris, L. Yang, A. Rida, A. Traille, R. Vyas, and T. Wu, "Inkjet-printed RFID tags on paper-based substrates for UHF 'cognitive intelligence' applications," in *Proceedings of the 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '07)*, pp. 1–4, Athens, Greece, September 2007.

[6] S. L. Merilampi, J. Virkki, L. Ukkonen, and L. Sydänheimo, "Testing the effects of temperature and humidity on printed passive UHF RFID tags on paper substrate," *International Journal of Electronics*, vol. 101, no. 5, pp. 711–730, 2014.

[7] J. Virtanen, J. Virkki, L. Sydänheimo, M. M. Tentzeris, and L. Ukkonen, "Automated identification of plywood using embedded inkjet-printed passive UHF RFID tags," *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 3, pp. 796–806, 2013.

[8] J. Virkki, S. Merilampi, L. Ukkonen, and L. Sydänheimo, "Performance of UHF RFID tags printed directly on plywood structures," *International Journal of RF Technologies*, vol. 3, no. 4, pp. 283–302, 2012.

[9] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*, John Wiley & Sons, Chichester, UK, 2nd edition, 2003.

[10] G. Marrocco, "Pervasive electromagnetics: sensing paradigms by passive RFID technology," *IEEE Wireless Communications*, vol. 17, no. 6, pp. 10–17, 2010.

[11] E. Welbourne, L. Battle, G. Cole et al., "Building the internet of things using RFID," *IEEE Internet Computing*, vol. 13, no. 3, pp. 48–55, 2009.

[12] J. Landt, "The history of RFID," *IEEE Potentials*, vol. 24, no. 4, pp. 8–11, 2005.

[13] R. Want, "An introduction to RFID technology," *IEEE Pervasive Computing*, vol. 5, no. 1, pp. 25–33, 2006.

[14] D. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*, Newnes-Elsevier, 2008.

[15] G. Marrocco, "The art of UHF RFID antenna design: impedance-matching and size-reduction techniques," *IEEE Antennas and Propagation Magazine*, vol. 50, no. 1, pp. 66–79, 2008.

[16] E. Perret, S. Tedjini, and R. S. Nair, "Design of antennas for UHF RFID tags," *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2330–2340, 2012.

[17] J. Virkki, S. Merilampi, L. Ukkonen, and L. Sydänheimo, "Performance of UHF RFID tags printed directly on plywood structures," *International Journal of RF Technologies: Research and Applications*, vol. 3, no. 4, pp. 283–302, 2012.

[18] Metalon HPS-021LV Silver Screen Ink, April 2016, http://store novacentrix.com/v/vspfiles/assets/images/metalon%20hps-021lv_2230.1.pdf.

[19] Metalon ICI-021 Copper Oxide Screen Ink, April 2016, https://store.novacentrix.com/v/vspfiles/assets/images/metalon%20ici-021%202229.1.pdf.

[20] H.-S. Kim, S. R. Dhage, D.-E. Shim, and H. T. Hahn, "Intense pulsed light sintering of copper nanoink for printed electronics," *Applied Physics A: Materials Science & Processing*, vol. 97, no. 4, pp. 791–798, 2009.

[21] B. Polzinger, F. Schoen, V. Matic et al., "UV-sintering of inkjet-printed conductive silver tracks," in *Proceedings of the 11th IEEE International Conference on Nanotechnology (NANO '11)*, pp. 201–204, Portland, Ore, USA, August 2011.

[22] J. Ryu, H.-S. Kim, and H. T. Hahn, "Reactive sintering of copper nanoparticles using intense pulsed light for printed electronics," *Journal of Electronic Materials*, vol. 40, no. 1, pp. 42–50, 2011.

[23] S.-H. Park, W.-H. Chung, and H.-S. Kim, "Temperature changes of copper nanoparticle ink during flash light sintering," *Journal of Materials Processing Technology*, vol. 214, no. 11, pp. 2730–2738, 2014.

[24] Xenon Sinteron 2010-L Installation and User Manual, Xenon Corporation, 2013.

[25] K. A. Schroder, S. C. McCool, and W. F. Furlan, "Broadcast photonic curing of metallic nanoparticle films," in *Proceedings of the NSTI Nanotechnology Conference and Trade Show*, vol. 3, pp. 198–201, Boston, Mass, USA, May 2006.

[26] S. Lim, M. Joyce, P. D. Fleming, and A. T. Aijazi, "Inkjet printing and sintering of nano-copper ink," *Journal of Imaging Science and Technology*, vol. 57, no. 5, pp. 50506-1–50506-7, 2013.

[27] D. J. Lee, S. H. Park, S. Jang, H. S. Kim, J. H. Oh, and Y. W. Song, "Pulsed light sintering characteristics of inkjet-printed nanosilver films on a polymer substrate," *Journal of Micromechanics and Microengineering*, vol. 21, no. 12, Article ID 125023, 2011.

[28] NXP UCODE G2iL IC, April 2016, http://www.nxp.com/documents/data_sheet/SL3S1203_1213.pdf.

[29] Voyantic Ltd., Espoo, Finland, May 2015, http://www.voyantic.com/.

PUBLICATION II

Reliability of Passive UHF RFID Copper Tags on Plywood Substrate in High Humidity Conditions

Erja Sipilä, Johanna Virkki, Lauri Sydänheimo, and Leena Ukkonen

Department of Electronics and Communications Engineering, Tampere University of Technology, P.O.Box 692, FI-33101 Tampere, Finland

Phone +358 40 8490103 and E-mail erja.sipila@tut.fi

Abstract

The growth of the wireless world, especially the increasing popularity of the Internet of Things, has created a need for cost-effective and environmentally friendly electronics. Great potential lies especially in versatile applications of passive UHF RFID components. However, the reliability of these components is a major issue to be addressed. This paper presents a preliminary reliability study of glue-coated and non-coated brush-painted copper tags on a plywood substrate in high humidity conditions. The passive UHF RFID components presented in this paper are fabricated using brush-painting and photonic sintering of cost-effective copper oxide ink directly on a plywood substrate. The performance of the glue-coated and non-coated tags is evaluated through wireless tag measurements before and after high humidity testing. The measurement results show that the copper tags on plywood substrate initially achieve peak read ranges of 7-8 meters and the applied coating does not affect to the read range. Moisture does not prevent the coated tags from working in a tolerable way, although the tag performance slightly temporarily decreases due to the moisture absorption. However, when the moisture exposure is long, the performance degradation comes irreversible. The absorbed moisture decreases the read range of the non-coated tags and the performance does not return back to normal after drying. Hence, the coating improves the reliability of the tags in a moist environment compared to the non-coated tags. Based on our results, the plywood material and the used manufacturing methods are very potential for low-cost, high-volume green electronics manufacturing.

Key words: brush-painting, copper ink, photonic sintering, plywood, RFID, wood

Introduction

The desire to integrate electronics into environmentally friendly structures increases together with the popularity of the Internet of Things (IoT). The future IoT demands a massive amount of wireless identification and sensing systems. One very attractive technology to fulfill the needs of the IoT is passive ultra high frequency (UHF) radio frequency identification (RFID). This battery-free technology uses remotely addressable electronic tags composed of an antenna and an integrated circuit (IC) by using propagating electromagnetic waves. The passive UHF RFID technology is already widely used, e.g., in logistics, retail stores, libraries, and transportation. Nowadays the most used manufacturing method for passive UHF RFID components is chemical etching with polymer substrates (e.g. polyimide and polyethylene terephthalate). However, this method is not suitable for new substrate materials, e.g., wood-based materials. In addition, etching is not an environmentally friendly method, and the green values are becoming more and more important in every field of manufacturing. Another issue to be pointed out is that together with the increasing amount of identification and sensing tags in the IoT, also the amount of electronics waste rapidly increases. Thus, the use of green materials and manufacturing methods in RFID tag manufacturing is extremely important, when considering the ever increasing amount of electronics waste, which causes serious environmental concerns [1].

Wood is an environmentally friendly and biodegradable material that has a huge potential as a cost-effective substrate material in various electronics applications. The passive UHF RFID tags presented in this paper are fabricated using brush-painting and photonic sintering of cost-effective copper oxide ink directly on a plywood substrate to be embedded into wooden structures. This manufacturing method eliminates the need of a separate substrate when the item itself acts as the substrate, thus reducing the amount of needed materials altogether, and also the number of process steps is reduced.

In addition, part of the manufactured tags is glue coated after manufacturing in order to study the effect of coating on the tag reliability in humid environment. The effects of humidity on the tag performance are examined with 100% relative humidity (RH) tests. The wireless performance of the tags is evaluated in normal room conditions, after two different 100% RH tests, lasting for 5 minutes and 1 hour, and after drying for 3 days in normal room conditions.

Brush-painting

Brush-painting is an additive antenna manufacturing method, which resembles screen-printing. In brush-painting the conductive ink is applied with a brush directly on the substrate, only onto the places where the conductive pattern shoud be. A stencil is needed, especially when small dimensioned patterns are manufactured. Brush-painting has been previously successfully used in tag manufacturing on plywood substrate with silver and copper nanoparticle inks [2] and with screen printable silver ink [3].

Photonic Sintering

Photonic sintering is a very attractive sintering method, especially when considering low-cost and high-volume production. The sintering is done using a xenon flash lamp in normal room conditions. The light energy in transferred to heat energy in the surface of the conductive ink, and the ink is sintered and this way an electrically conductive structure is formed. The process time of photonic sintering is only milli- or microseconds [4], which is a huge advantage compared to widely used heat sintering, which can take tens of minutes. In addition, photonic sintering is suitable to heat sensitive materials, e. g. wood, paper and many low-cost polymers. In photonic sintering only the ink is very rapidly heated. The substrate is not absorbing light energy and transforming it to heat energy. In addition, because the sintering process is very fast, the heat energy from ink does not significantly transfer to the substrate.

The energy from each flash pulse in photonic sintering can be calculated using the following formula:

$$E = \left(\frac{V}{3120}\right)^{2.4} \cdot t, \qquad (1)$$

where E is the energy in Joules per pulse, V is the voltage in Volts and t is the time in micro seconds [5].

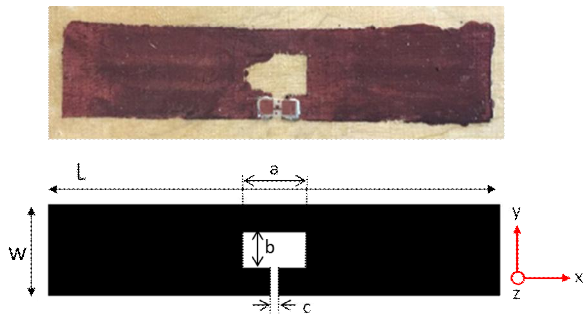
The photonic sintering of copper oxide inks has been found to be much more challenging than the photonic sintering of silver inks [6]. The copper oxide is not conducting, but the silver oxide is. On the other hand, it has been found that during the photonic sintering process the copper oxide reduces to copper [7]. The copper oxide ink can be successfully photonically sintered, but the sintering parameters need to be carefully tested for each ink and substrate material combination.

Conformal Coatings

As RFID tags are the critical enabling components of various wireless systems, they often operate in an extremely challenging environment, which requires them to endure different environmental stresses, such as high humidity. The humid environment is a challenge to a wood substrate. Wood absorbs moisture easily, and moisture affects its electrical and mechanical properties [8, 9]. For this reason electronics on a wood substrate or embedded inside wooden layers should be coated in order to increase the structure's tolerance to moisture. Many different kinds of conformal coatings can be used, e.g., epoxy, silicone, acrylic, polyurethane and parylene materials [10]. Especially epoxy is widely used in electronics because of its relatively low price combined with ease of processing, and excellent electrical, mechanical, thermal and moisture protection properties [1, 11].

Manufacturing of the Samples

In this study, cost-effective copper oxide ink (Metalon ICI-021 copper oxide ink [12]) was used. The tag antennas were brush-painted through a stencil (50 µm thick polyimide) on 4 mm thick birch plywood. Figure 1 shows the antenna design and a ready copper tag and Figure 2 shows a cross section of the used plywood material.



Geometrical parameters in millimeters

L	W	a	b	C
100	20	14.3	8.125	2

Figure 1: A ready copper tag (top) and the used antenna geometry (bottom).

Figure 2: A cross-section of the plywood substrate (thickness is 4mm).

In this study the used photonical sintering parameters were 2000 µs, 2400 V, and 2 flash pulses, the energy with these sintering parameters from the flash lamp calculated using Equation 1 is 2.1 kJ. These optimal sintering parameters for this ink and material combination were found in a previous systematic study [6]. In this study 2 flash pulses were used in order to confirm the thorough sintering result of the sample before high humidity exposure. A microscope image of the ready copper surface on plywood is presented in Figure 3.

The diagonal resistances immediately after tag antenna manufacturing are presented in Table 1. The resistances from antenna corner to corner have been measured with a Fluke 111 True RMS multimeter and the measured antenna resistances were in the range of 5.8 to 8.1 ohms. The resistances of antennas with the same design, which were fabricated with screen printable silver ink on the same substrate, have been measured to be in the range of 2 to 6 ohms [3]. The resistances of these copper antennas are thus in a good level as they are comparable to the resistances of silver antennas.

The tag chip utilized in this study was NXP UCODE G2iL series IC, which the manufacturer of the chip has mounted on a strap. We connected the strap to the antenna terminals using conductive epoxy (Circuit Works CW2400). Finally, half of the manufactured tags were coated with water-proof textile glue (Gutermann Creativ HT2).

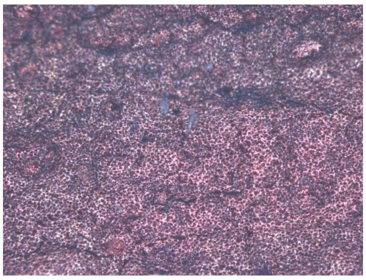


Figure 3: A microscope image (5x magnification) of a ready copper surface on plywood.

Table 1: Diagonal resistances of the samples (Ω).

Sample 1	Sample 2	Sample 3	Sample 4
5.8	6.4	6.8	8.1

Humidity Testing and Wireless Measurements

In order to find out the humidity absorbtion of the tags, the weights of the tags in normal room conditions, after two different 100% RH tests, lasting for 5 minutes and 1 hour, and after drying for 3 days in normal room conditions, were measured. The temperature in these test conditions was normal office temperature. The exact temperature in the office was not measured at the test time. The results are shown in Table 2. The sample weights were measured using Sartorius Extend ED124S precision scale. The accuracy of this scale is 0.1 mg, and it gives the result with 5 digits. The weight changes in Table 2 are in percents, and the weight is compared to the initial results for the non-coated samples and to the after-coating results for the coated samples. The weights after drying for 3 days in office conditions are very near to the initial values, indicating that the moisture has dried off almost completely.

Table 2: Tag weight measurements.

	5 min moisture	**1 h moisture**	**After drying**
Non-coated	+ 9.37 %	-	+ 0.05 %
Non-coated	-	+ 18.70 %	´+ 0.22 %
Coated	+ 7.13 %	-	+ 0.23 %
Coated	-	+ 20.34 %	+ 1.02 %

Voyantic Tagformance RFID measurement system was used to test the wireless performance of the tags in different conditions. We recorded the minimum transmitted power from the reader to activate the tag (threshold power) between 800 MHz - 1 GHz. The attainable free-space read range (d_{tag}), or theoretical read range, of the tag was used to provide universal tag characterization. The d_{tag} can be calculated based on the measured threshold power of the tag under test and a system reference tag as:

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}\ , \qquad (2)$$

where λ is the wavelength transmitted from the reader, effective isotropic radiated power (EIRP) is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, Λ is a known parameter (unit: watts) describing the sensitivity of the reference tag of the measurement system, P_{th*} is the measured threshold power of the reference tag, and P_{th} is the measured threshold power of the tag under test. In this article, all the read range results are reported under the European RFID emission regulation.

The read ranges of the non-coated and glue-coated samples were measured after manufacturing, after coating, after exposure to 100% RH, and after 3 days in normal office conditions. The results are presented in Figures 4-7, where the tag’s theoretical read range can be seen according to frequency. In general the UHF RFID tags are designed to have a clear peak frequency, in Europe this peak frequency is 865.6 MHz - 867.6 MHz. In this study the d_{tag} measurements have been done covering the whole global UHF RFID frequency band (860 MHz - 960 MHz). The most interesting information in Figures 4-7 is the European UHF RFID peak frequency, and how long the d_{tag} is in that frequency. In addition, in

Figures 4-7 interesting is also the change in d_{tag} according to tag's coating process or humidity exposure, in other words interesting is, how these affect to the d_{tag}. It is seen in Figures 4-7 that the tags manufactured in this study have good theoretical read ranges, initially over 4 meters, throughout the global UHF RFID band.

Initially all the tags achieve peak read ranges of 7-8 meters, which is well enough for most normal RFID applications. As can be seen in Figure 5 and Figure 6, the coating process and the used coating material does not have a significant effect on the read range of the tags.

It can be expected that the exposure to high humidity conditions will have an effect on the tag performance. The absorbed moisture can affect the impedance matching of the tag, as well as the dielectric constant and loss tangent of the plywood substrate [13]. As can be seen, the exposure to 100% RH reduces the d_{tag} of the non-coated tags significantly, which can be seen in Figures 4 and 5. In addition, the performance does not return back to initial after drying. The coated tags seem to endure 5 minutes exposure to 100% RH quite well, as it only causes a shift of the peak dt_{ag} to a lower frequency, and the d_{tag} returns back to initial after drying. This is shown in Figure 6. However, 1 hour exposure to 100% RH seems to cause a permanent slight decrease of the d_{tag} even for the coated tags. This is seen in Figure 7. The weight measurement results in Table 2 show that the moisture content after drying for 3 days is almost the same as before the moisture exposure, which indicates that moisture causes irreversible changes to the tag performance.

Both glue-coated and non-coated silver tags on the same substrate material have been found to recover after drying [3]. This indicates that the copper oxide ink is not as reliable in high humidity conditions as the silver ink. However, these humidity tests were very extreme, and the performance of the coated tags after 5 minutes in high humidity can still be considered to be suitable. In addition, copper oxide ink is more cost-effective, and it could definitely be an option for silver ink in dry environments.

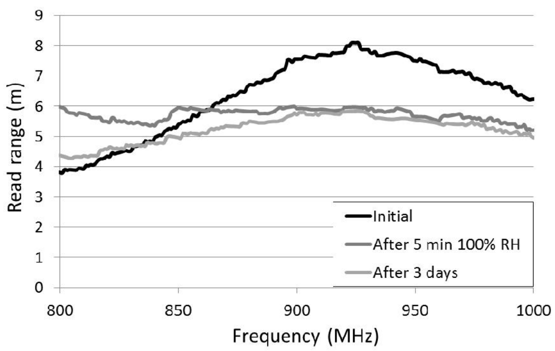


Figure 4: Measured read range for a non-coated tag after 5 min exposure for 100% RH.

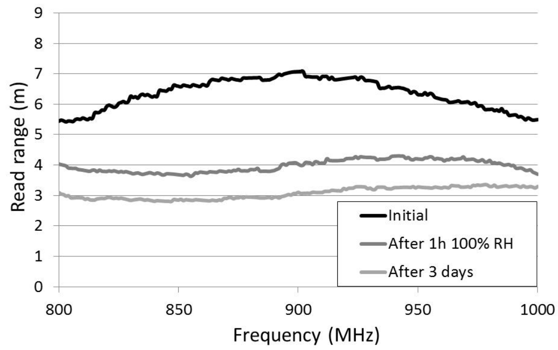


Figure 5: Measured read range for a non-coated tag after 1 h exposure for 100% RH.

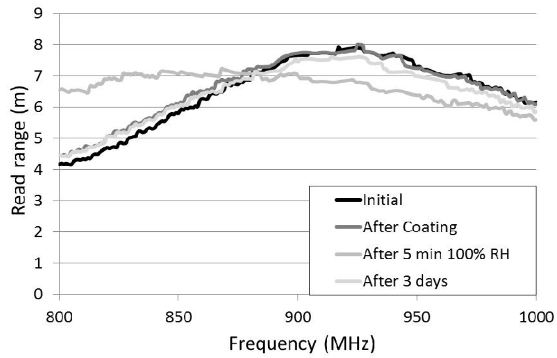


Figure 6: Measured read range for a glue-coated tag after 5 min exposure for 100% RH.

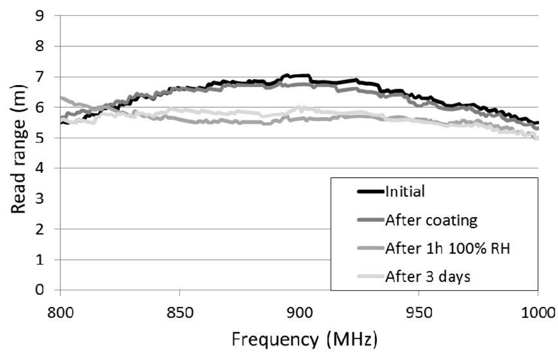


Figure 7: Measured read range for a glue-coated tag after 1 h exposure for 100% RH.

Conclusion

This paper presented a reliability study of glue-coated and non-coated brush-painted and photonically sintered passive UHF RFID copper tags on a plywood substrate in high humidity conditions. According to our results, brush-painting and photonical sintering can be used to effectively fabricate environmentally friendly passive UHF RFID tag antennas. The high humidity conditions did not prevent the glue-coated tags from working, although their wireless performance was temporary slightly decreased due to the absorbed moisture. The moisture had a stronger effect on the wireless performance of the non-coated tags and they cannot be considered to be suitable for high humidity conditions.

Acknowledgements

This research was funded by The Academy of Finland, Jane and Aatos Erkko Foundation, Emil Aaltonen Foundation, Ulla Tuominen foundation, KAUTE foundation, Jenny and Antti Wihuri foundation and TEKES.

References

[1] Y. H. Jung, T.-H. Chang, H. Zhang, C. Yao, Q. Zheng, V. W. Yang, H. Mi, M. Kim, S. J. Cho, D.-W. Park, H. Jiang, J. Lee, Y. Qui, W. Zhou, Z. Cai, S. Gong, Z. Ma, “High-performance green flexible electronics based on biodegradable cellulose nanofibril paper”, Nature Communications, Vol. 6, Article number 7170, 11 p., May, 2015.

[2] E. Sipilä, J. Virkki, L. Sydänheimo, L. Ukkonen, “Experimental Study on Brush-Painted Metallic Nanoparticle UHF RFID Tags on Wood Substrates”, IEEE Antennas and Wireless Propagation Letters, Vol. 14, pp. 301-304, February, 2015.

[3] E. Sipilä, J. Virkki, L. Sydänheimo, L. Ukkonen, “Experimental Study on Brush-Painted Passive RFID Based Humidity Sensors Embedded into Plywood Structures”, International Journal of Antennas and Propagation, Vol. 2016, Article ID 1203673, 8 p., January, 2016.

[4] H. Kang, E. Sowade, R. R. Baumann, “Direct intense pulsed light sintering of inkjet-printed copper oxide layers within six milliseconds”, ACS Applied Materials & Interfaces, Vol. 6, No. 3, pp. 1682-1687, January, 2014.

[5] Xenon Sinteron 2010-L Installation and User Manual, Xenon Corporation, 2013.

[6] E. Sipilä, J. Virkki, J. Wang, L. Sydänheimo, L. Ukkonen, ”Brush-painting and Photonical Sintering of Copper Oxide and Silver Inks on Wood and Cardboard Substrates to Form Antennas for UHF RFID Tags”, Accepted for publication in International Journal of Antennas and Propagation. In press.

[7] S.-J. Joo, S.-H. Park, C.-J. Moon, H.-S. Kim, ”A Highly Reliable Copper Nanowire/Nanoparticle Ink Pattern with High Conductivity on Flexible Substrate Prepared via a Flash Light-Sintering Technique”, ACS Applied Materials and Interfaces, Vol. 7, No. 10, pp. 5674-5684, February, 2015.

[8] W. Li, J. Van den Bulcke, I. De Windt, J. Dhaene, J. Van Acker, “Moisture behaviour and structural changes of plywood during outdoor exposure”, European Journal of Wood and Wood Products, Vol. 74, No. 2, pp. 211-221, November, 2015.

[9] S. V. Glass, S. L. Zelinka, ”Moisture relations and physical properties of wood, Wood handbook: wood as an engineering material: chapter 4”, Centennial ed. General technical report FPL; GTR-190. Madison, WI: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, pp. 4.1-4.19, 2010.

[10] E. Halonen, V. Pynttäri, J. Lilja, H. Sillanpää, M. Mäntysalo, J. Heikkinen, R. Mäkinen, T. Kaija, P. Salonen, ”Environmental protection of inkjet-printed Ag conductors”, Microelectronics Engineering, Vol. 88, No.9, pp. 2970-2976, September, 2011.

[11] James J. Licari, “Coating Materials for Electronic Applications, Polymers, Processes, Reliability, Testing”, William Andrew Publishing, Norwich, New York, Chapter 2, pp. 65-200, 2003.

[12] Metalon ICI-021 Copper Oxide Screen Ink. https://store.novacentrix.com/v/vspfiles/assets/images/metalon%20ici-021%202229.1.pdf. Accessed April 2016.

[13] J. Virkki, S. Merilampi, L. Ukkonen, L. Sydänheimo, “Performance of UHF RFID Tags Printed Directly on Plywood Structures”, International Journal of RF Technologies: Research & Applications, Vol. 3, No. 4, pp. 283-302, January, 2012.

PUBLICATION III

Additive Manufacturing of Antennas from Copper Oxide Nanoparticle Ink: Toward Low-Cost RFID Tags on Paper- and Textile-based Platforms

Erja Sipilä[1], Jun Liu[2], Jianhua Wang[2], Johanna Virkki[1], Toni Björninen[1], Lianglun Cheng[2], Lauri Sydänheimo[1], Leena Ukkonen[1]

[1] Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere, Finland
erja.sipila@tut.fi

[2] Faculty of Automation, Guangdong University of Technology, Guangzhou, China

***Abstract*—We outline the possibilities of 3D direct write dispensing and brush-painting in the manufacturing of copper UHF RFID tags on textile and cardboard materials and present considerations regarding the process parameters to achieve high-performance tags when the copper antenna is deposited directly on these rough and porous materials. Our measurement results confirm that the additively-manufactured copper RFID tags on environmental-friendly substrates achieve high performance with the attainable theoretical read ranges of 3.5-to-8.5 meters in air.**

***Index Terms*—3D dispensing, UHF RFID, photonical sintering, textile antennas, cardboard, copper ink**

I. Introduction

The number of wireless devices is increasing rapidly, and in the near future the number is expected to explode, especially caused by the development of the Internet of Things (IoT). Due to the massive increase in the number of wireless devices, the material choices in future applications will have a huge effect on the environment. Thus, the use of biodegradable, environmental-friendly materials, e.g., cardboard, textile, wood, and paper, together with additive manufacturing methods, has been a growing trend in electronics during the recent years [1-4].

Passive RFID (radio frequency identification) technology provides the automatic identification and tracking of items. This is achieved with battery-free remotely addressable electronic tags composed of an antenna on a substrate and an integrated circuit (IC). The use of propagating electromagnetic waves in the UHF (ultra high frequency) regime for powering and communicating with the passive tags enables rapid interrogation of a large quantity of tags through various media. In comparison to bar-codes and chipless RFID tags, IC-enabled tags allow the data stored in them to be updated and read wirelessly at any time. Thanks to the energy efficient mechanism of digitally modulated scattering utilized in the tag-to-reader wireless communication, the data can be read from the distance of several meters and specialized antennas can provide reading distances reaching 25 meters without an on-board energy source. This makes the battery-free passive RFID tags promising candidates as sensing platforms and digital entities in the IoT [5].

II. Tag Manufacturing Methods

In this work, we present 3D direct write dispensing and brush-painting of screen-printable copper oxide ink (Novacentrix Metallon ICI-021) [6] to form antennas on 100% cotton fabric and pulsed-light sintering of the deposited ink. We will compare the tags on textile substrate to a tag on cardboard substrate, which was manufactured using the same brush-painting and pulsed-light sintering process.

For the purpose of this study, we chose the tag antenna to be a simple dipole (Fig. 1). This geometry was originally developed to be used on demanding substrate materials, which have uneven, porous, or much ink absorbing surfaces and the antenna geometry has been successfully used with both fabrication methods with nanoparticle silver and copper inks and screen printing silver ink [3, 4].

A. 3D Direct Write Dispensing

We used nScrypt tabletop series 3D direct write dispensing system to fabricate the copper antennas on 100% cotton material. The system offers a computer controlled platform to drive precision dispensing pumps. Three-axis motion control system allows the deposition not only on planar surfaces but also onto 3D surfaces with the precision meeting the requirements of modern mobile communication antennas [7]. The printed pattern can be imported from regular computer aided design software. The dispensing pump consists of a positive pressure pump with a computer-controlled needle valve. The air pressure applied to the syringe barrel containing the ink (See Fig. 2) is also computer controlled. The pressure pushes the ink into the main valve body and the needle valve is opened and closed to regulate the ink flow pushed into the ceramic nozzle tip by the pressure. In addition to pressure, the velocity at which the nozzle tip moves and the distance between the nozzle tip and the substrate are important process parameters. Moreover, the diameter of the nozzle tip should be chosen according to the desired print resolution and viscosity of the material which is being deposited. In our previous study it was found that the best 3D direct write printing result on textile substrate is achieved when the nozzle tip is lowed so low that it slightly squeezes the fabric [8]. 3D direct write dispensing has been previously used to fabricate UHF RFID tag antennas on fabric substrate with screen-printable silver ink [4,8] and copper oxide ink [8].

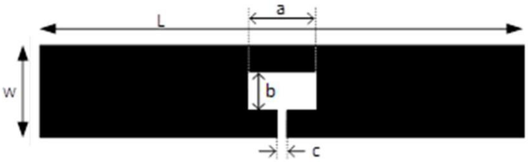
B. Brush-painting

Brush-painting is a versatile, simple and fast manufacturing method that includes only two process steps: brushing and sintering. Brush-painting has been previously successfully used for fabrication of UHF RFID tag antennas on fabric substrate with silver nanoparticle ink [2] and on wood substrate with silver and copper nanoparticle inks [3]. In this study, copper antennas were brush-painted through a stencil (50 µm thick polyimide film) on packaging cardboard and 100% cotton textile substrates, by using only one layer of ink.

C. Photonical Sintering

The sintering method in this study was photonical sintering with xenon flash lamp. The photonical sintering has many advantages compared to commonly used heat sintering, e.g., very fast process time (micro- or milliseconds); suitability to heat sensitive substrate materials; no need for chemicals or vacuum, or other special process athmosphere; and different kinds of materials, both substrates and inks, can be used in the same system. The photonical sintering in this study was done using a Xenon Sinteron 2010-L system, which provides a high energy pulsed light for sintering of conductive particles.

In addition to commonly used silver inks, the photonical sintering is applicable on the more cost-effective copper inks, which cannot be sintered by heat sintering in normal room atmosphere due to the rapid oxidation of copper.



Geometrical parameters in millimeters

L	W	a	b	c
100	20	14.3	8.125	2

Fig. 1. Utilized tag antenna geometry.

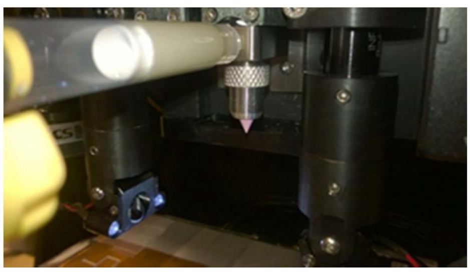


Fig. 2. The 3D direct write dispensing device. The ink cartridge and nozzle tip attached to the dispenser.

The photonical sintering system parameters are lamp voltage, flash pulse duration, and number of flash pulses. The lamp voltage can be adjusted between 1800 V and 3000 V, in 50 V increments, and the pulse duration can be adjusted up to 2000 µs, which was used as pulse duration in this study. The sintering parameters depend very much on the materials in use, both the ink material as well as the substrate material.

The copper antennas deposited on fabric substrate by 3D direct write dispensing were found to be optimally sintered with a voltage of 2200 V and two flash pulses. The copper antennas brush-painted on fabric substrate were found to be optimally sintered with a voltage of 2800 V using four flash pulses. The sintering voltage for brush-painted tag on cardboard was 2200 V and 1 flash pulse was enough.

The sintering parameters for each substrate were chosen after a preliminary study. As can be seen from the sintering parameters, they need to be chosen individually for each fabrication method, ink, and substrate. The energy transferred from each flash pulse from the sintering machine can be calculated using:

$$E = \left(\frac{V}{3120}\right)^{2.4} \cdot t, \qquad (1)$$

where E is the energy in Joules per pulse, V is the voltage in Volts and t is the time in micro seconds [9]. The transferred energies for the different manufacturing parameters are presented in table 1.

When comparing textile and cardboard substrate materials, it can be seen from sintering parameters, that the cardboard needs fewer flash pulses than the textile substrate. So, less energy is needed for the sintering on cardboard than on textile material, which can be seen also in Table 1. This is probably due to the more even and uniform surface of the cardboard. In addition, when comparing the sintering parameters and transferred energies in Table 1 on textile material with different fabrication methods, it can be seen that with 3D dispensing lower energy is enough than with brush-painting. This comes along with the thickness of the ink, with 3D dispensing the ink layer thickness is smaller than with brush-painting.

D. Tag IC

The tag IC we used was NXP UCODE G2iL series RFID IC [10] with the wake-up power of −18 dBm (15.8 µW). It was provided by the manufacturer in a carrier fixture patterned from copper on a plastic film. We attached the 3 x 3 mm^2 pads of the fixture to the antenna with conductive silver epoxy. The ready-made brush-painted and 3D deposited copper tags on fabric and cardboard substrates are shown in Fig. 3.

TABLE I. TRANSFERRED ENERGIES IN PHOTONICAL SINTERING

3D dispensed on textile	**Brush-painted on textile**	**Brush-painted on cardboard**
1.7 kJ	6.2 kJ	0.9 kJ

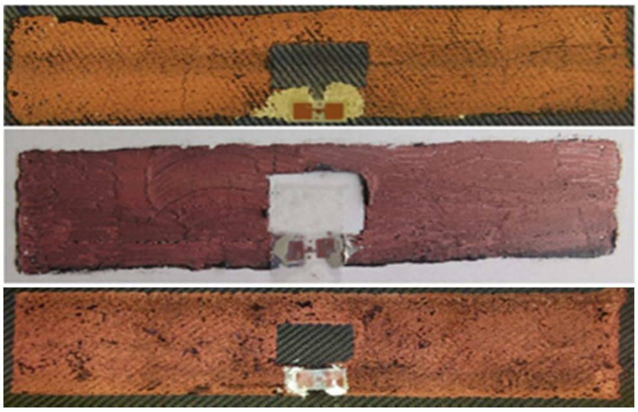


Fig. 3. The manufactured tags: brush-painted on fabric (top), brush-painted on cardboard (middle) and 3D dispensed on fabric (bottom)

III. Evaluation of the UHF RFID Tag Performance

All of the measurements were performed using a Tagformance RFID measurement unit. The core operations are performed with a vector signal analyzer. Two key properties of passive UHF RFID tags, threshold power and theoretical read range, were measured as a function of transmit frequency.

Threshold power describes the minimum transmit power, at the transmit port, to activate the tag and can be expressed as:

$$P_{TS} = \frac{P_{IC}}{G_{tx} G_{tag} \tau \left(\frac{\lambda}{4\pi d}\right)^2 \left|\hat{p_{tx}} \cdot \hat{p_{tag}}\right|^2}, \tag{2}$$

where P_{IC} is the sensitivity of the RFID IC, G_{tx} and G_{tag} are the gains of the reader and tag antenna, respectively, τ is the power transmission coefficient between the antenna and the IC, d is the distance between the tag and reader antenna, p_{tx} and p_{tag} are the unit electric field vectors of the transmitting antenna and tag antenna. The inner product of the electric field vectors describes the power loss due to possibly mismatched polarization planes between the reader and tag antenna.

Theoretical read range describes the maximal distance between the tag and reader antenna in an environment without reflections or external disturbances. The measurement system is able to calculate the theoretical read range of a tag using its measured threshold power along with the measured forward losses. The forward loss describes the link loss between the generator's output port to the input port of an equivalent isotropic antenna placed at the tag's location. The forward loss from the transmit port to the tag, is calculated using a reference tag during calibration. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels and can be calculated as:

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS} L_{fwd}}}, \tag{3}$$

where EIRP is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, P_{TS} and L_{fwd} are the measured threshold power and forward losses correspondingly. In all measurements, the dipole tag was aligned for polarization matching with a linearly polarized reader antenna.

The attainable read ranges of copper tags in the frequency range of 800-1000 MHz are presented in Fig 4. As seen from the results, the 3D direct write dispensed tag on fabric substrate has the peak read range of 3.5 meters while the brush-painted copper tags on fabric and cardboard substrates achieved the peak read ranges of 6 and 8.5 meters, respectively. The better performance of the brush-painted tag may be due to a thicker ink layer, providing a more uniform antenna surface. However, with 3D direct write dispensing, a more precise antenna, both in thickness as in antenna edge formation, can be achieved. If an antenna geometry with precise layout is used, the 3D direct write dispensing can do it. With brush-painting very narrow and precise antenna geometries are very difficult to manufacture.

The results presented in this study are very good, especially with copper oxide ink. In our previous work [2] the same antenna geometry, brush-painting process and substrate material were used with silver nanoparticle ink, and the peak read ranges were found to be about 2 meters. So, in this study, the brush-painted antennas manufactured using copper oxide ink has performed much better on 100% cotton fabric substrate. In addition, we have made 3D direct write dispensed antennas with the same antenna geometry and screen printable silver ink on fabric substrate in a previous study [4]. In that study the fabric was different compared to this study, and so was the sintering process. In [4] the fabric was a mixture of polyester and viscose and the used sintering method was heat sintering. The peak read ranges in [4] were over 8.5 meters. The results in this study with 3D direct write dispensing system are not as good as in [4], but the photonical sintering process is very much faster compared to the heat sintering, and the used copper oxide ink is cheaper than the silver ink in [4], so the 3D direct write dispensing with copper oxide ink and photonical sintering are a good choice for low-cost manufacturing. Overall, all the tags in this study showed read ranges suitable for the needs of the future wireless IoT applications and the copper oxide ink provides lower material costs compared to silver inks.

Fig. 5 shows a comparison of the attainable read ranges of several textile tags with antennas manufactured with different methods and materials. All antennas have the same shape detailed in Fig. 2. The silver and copper fabric tags were patterned from Less EMF Stretch Conductive Fabric (Cat #321) and Less EMF Pure Copper Polyester Taffeta Fabric (Cat #A1212) with scissors. The screen printed silver tag was formed from a polymer thick film (PTF) silver ink on stretchable, elastic band fabric substrate, following the procedure detailed in [11].

Based on the results of this study, 3D direct write dispensing and brush-painting are very efficient fabrication methods and very interesting choices when considering future antenna manufacturing and applications.

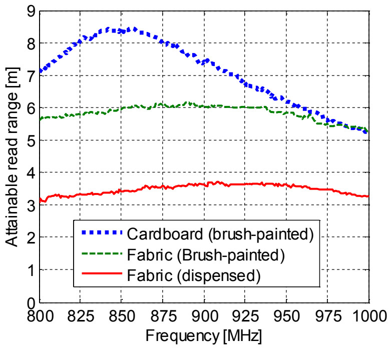


Fig. 4. Attainable read ranges of the manufactured tags under the European emission limit EIRP = 3.28W.

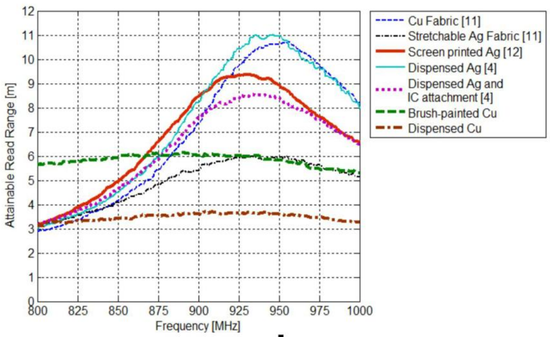


Fig. 5. Measured performance of various textile UHF RFID tags.

IV. CONCLUSION

We present a simple single-step brush-painting method and a 3D direct write dispensing method of depositing low-cost copper inks directly on fabric and cardboard substrates for environmental-friendly passive UHF RFID tag antennas. According to our wireless measurements, the performance of the copper tags on both the substrates we used is suitable for numerous future IoT applications. Especially with brush-painting a possibility to very low-cost RFID tag manufacturing is promising. As a future work, we will investigate the direct write dispensing and brush-painting of stretchable antennas and protective coatings, as well as new environmentally friendly substrate materials. In addition, we will investigate the behavior of copper ink antennas on environmentally friendly substrates under different environmental conditions, e. g. in high humidity.

REFERENCES

[1] S. Kim, R. Vyas, A. Georgiadis, A. Collado, and M.M. Tentzeris, "Inkjet-printed RF energy harvesting and wireless power trasmission devices on paper substrate," EuMC, Nuremberg, Germany, October 2013, pp. 983-986.

[2] J. Virkki, T. Björninen, L. Sydänheimo, and L. Ukkonen, "Brush-painted silver nanoparticle UHF RFID tags on fabric substrates," PIERS, Guangzhou, China, pp. 2106-2110, August 2014

[3] E. Sipilä, J. Virkki, L. Sydänheimo, and L. Ukkonen, "Experimental study on brush-painted metallic nanoparticle UHF RFID tags on wood substrates," IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 301-305, February 2015

[4] T. Björninen, J. Virkki, L. Sydänheimo, and L.Ukkonen, "Possibilities of 3D direct write dispensing for textile UHF RFID tag manufacturing," Published in IEEE APS Symp., Vancouver, Canada, July 2015

[5] G. Marrocco, "Pervasive electromagnetics: sensing paradigms by passive RFID technology," IEEE Wireless Commun., vol. 17,(6), pp. 10-17, December 2010

[6] Novacentrix Metalon ICI-021 copper oxide screen ink http://store.novacentrix.com/v/vspfiles/assets/images/metalon%20ici-021%202229.1.pdf, accessed June 2015

[7] P. Salonen, V. Kupiainen, and M. Tuohimaa, "Direct printing of a handset antenna on a 3D surface," IEEE APS Symp., Denver, Colorado, USA, pp. 504-505, August 2013

[8] T. Björninen, J. Virkki, L. Sydänheimo, and L.Ukkonen, "Manufacturing of antennas for passive UHF RFID tags by direct write dispensing of copper and silver inks on textiles," Published in ICEAA symp., Torino, Italy, pp. 589-592, September 2015

[9] Xenon Sinteron 2010-L, Installation and User Manual, Xenon Corporation, 2013

[10] NXP UCODE G2iL IC, http://www.nxp.com/documents/data_sheet/SL3S1203_1213.pdf, accessed June 2015

[11] Y. Y. Fu, Y. L. Chan, M. H. Yang, Y.-C. Chan, J. Virkki, T. Björninen, L. Sydänheimo, and L. Ukkonen, "Experimental study on the washing durability of electro-textile UHF RFID tags," IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 466–469, February 2015

[12] J. Virkki, T. Björninen, S. Merilampi, L. Sydänheimo, and L. Ukkonen, "The effects of recurrent stretching on the performance of electro-textile and screen-printed ultra-high-frequency radio-frequency identification tags," Text. Res. J., vol. 85,(3), pp. 294-301, February 2015

PUBLICATION IV

Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2016, Article ID 1203673, 8 pages
http://dx.doi.org/10.1155/2016/1203673

Research Article

Experimental Study on Brush-Painted Passive RFID-Based Humidity Sensors Embedded into Plywood Structures

Erja Sipilä, Johanna Virkki, Lauri Sydänheimo, and Leena Ukkonen

Department of Electronics and Communications Engineering, Tampere University of Technology, P.O. Box 692, 33101 Tampere, Finland

Correspondence should be addressed to Erja Sipilä; erja.sipila@tut.fi

Received 18 November 2015; Accepted 22 December 2015

Academic Editor: Jaume Anguera

The integration of electronics and wood is an interesting research area due to the increasing interest to add functionality into various wooden products. The passive RFID-based humidity sensor tag prototype, presented in this paper, is fabricated directly on plywood substrate to be embedded into wooden structures, by using brush-painting and photonic sintering of cost-effective silver ink. To the best of our knowledge, this is the first demonstration of brush-painted antennas as sensor elements. The developed sensor tag is fully passive and small in size, meaning it can be permanently enclosed into wooden structures. In addition, the sensor tag has all the functionalities of an ordinary passive UHF RFID tag, and a peak read range of about 10 meters. The sensor performance was evaluated in normal room conditions, after two 100% relative humidity tests, and after drying in normal room conditions for 9 days. According to the results, the fabricated UHF RFID-based humidity sensor tags have a great potential to be utilized in humidity sensing applications, and also in normal automatic identification and supply chain control of various wooden products. In addition, the first results of more cost-effective brush-painted copper UHF RFID tags on plywood substrate are presented.

1. Introduction

Embedding of electronics as a part of versatile structures is a growing trend, especially along the emerging paradigm of the Internet of Things (IoT) [1]. Many industries are interested in novel smart products with identification and sensing possibilities. In addition to logistics and supply chain control, great potential lies especially in the construction, packaging, and furniture industries, where wood is a typical material. This makes the integration of electronics and wood, especially plywood, a very interesting research area [2, 3].

Passive RFID (radio-frequency identification) technology provides automatic identification and tracking of products achieved with battery-free remotely addressable electronic tags composed of an antenna and an integrated circuit (IC) on a substrate. Electromagnetic waves are used by an RFID reader and an RFID tag to communicate with each other. Furthermore, the electromagnetic waves sent by the reader are used to provide operating power for passive RFID tags as they have no power supply of their own. The use of propagating electromagnetic waves in the UHF (ultra high frequency) frequency range for powering and communicating with the passive tags enables rapid interrogation of a large quantity of tags through various media. Unlike barcodes, the IC-enabled tags allow the data stored in them to be updated or read wirelessly at any time. Thanks to the energy efficient mechanism of digitally modulated scattering utilized in the wireless communication, the tags can be read from a distance of several meters [4, 5]. This makes the passive tags favourable to be used for energy-autonomous wireless sensing platforms, for example, as strain, temperature, and humidity sensors that exhibit low complexity and cost [6–9]. It is possible to establish maintenance-free embeddable sensor components into different kinds of structures without the need for external sensors or on-board electronics, by using a passive UHF RFID tag antennas as the sensing element. Antenna-based sensing provides integration of sensing capabilities in passive RFID tags with a minimal increase in the overall complexity and power consumption of the tag.

One of the most interesting sensor types for passive RFID systems is a humidity sensor, which is due to the great number of materials reacting to humidity-level variations. In addition, the information about possible existing humidity or knowing the humidity level is essential in various application areas, including the construction industry, warehousing, and transportation. Previously, humidity sensor prototypes have been developed for UHF RFID systems [8, 10–12] by using traditional photolithography, as well as inkjet and screen printing.

The passive humidity sensor tag, which is presented in this paper, is fabricated directly on plywood substrate by using brush-painting and photonic sintering of cost-effective silver ink. The sensor tag is still at a prototyping stage but the tag is intended to be used for structural humidity monitoring, for example, inside wooden floors and walls, or to sense humidity conditions during transportation. The sensor tag can be used to quickly detect increased humidity level, thus dramatically reducing the amount of additional damage caused by continued humidity exposure. The sensor tag is fully passive, does not need any maintenance procedures, and can be permanently enclosed inside walls, ceilings, floors, and wooden containers for long-term monitoring. In addition, the sensor tag is small in size, allowing fitting inside various structures. This sensor tag also has all the functionalities of an ordinary passive RFID tag, which allows the use of several sensor tags in a small area, as they can be recognized using their unique identification codes. The tags can also be used for automatic identification and supply chain control of the wooden products.

The work presented here is organized as follows: after Introduction, Section 2 introduces the characteristics of used birch plywood. Section 3 introduces our tag design, the used brush-painting and sintering methods, and presents the tag fabrication with the optimized fabrication parameters. The wireless tag measurements and humidity absorption tests are introduced in Section 4. Section 5 presents the results and Section 6 summarizes the conclusions of this study.

2. Characteristics of Birch Plywood

Plywood is characterised by its high planar shear strength and impact resistance, excellent surface hardness, wear resistance, and creep resistance. Other good characteristics of birch plywood include being flexible and bendy, being strong and durable, easy working properties, good gluing properties, being ecological and biodegradable, and not to forget the beauty of its surface [13]. All these properties make birch much used and loved material, for example, in building and furniture industries.

Plywood has excellent dimensional stability under heat. In practice, the thermal deformation of plywood is so small that it can generally be disregarded. Standard Finnish plywood and most coated plywood products are suitable for use at temperatures of 100°C and many up to 120°C. Plywood endures cold even better than heat and can be used at sustained temperatures as low as −200°C. Although plywood burns, it can have better fire resistance than many materials which do not burn. The temperature at which plywood will ignite when exposed to a naked flame is about 270°C and to cause spontaneous combustion, a temperature of over 400°C is needed [13]. Thus, the temperature area of plywood is very suitable for the fabrication methods used in this study.

Like all other wood-based materials, plywood is a hygroscopic product and exhibits viscoelastic mechanical behavior. An increase in moisture content will result in a decrease in the strength, modulus of elasticity, and shear modulus values. Thus, also for these reasons, it is necessary to take the moisture conditions into consideration when using plywood.

3. Fabrication of the Tags

Brush-painting is a versatile but simple and fast additive manufacturing method. The method not only reduces the process-steps of RFID tag manufacturing, but also minimizes the need of conductive ink material, as the material is dispensed directly to the brush and from the brush directly to the antenna area in the substrate. By brush-painting RFID tags directly on plywood, we can manufacture very thin tags through eliminating the need for additional substrate material. The thickest part of the tag in this case is the IC, which determines the scale of the thickness of the tag. In our case the thickness of the IC is 120 μm [14], but the use of even thinner ICs, for example, 75 μm, is possible, meaning that embedding the tags inside versatile products is convenient. In addition, when the tags are embedded as a part of the wooden product, they will be almost impossible to remove from the product without breaking it, as the wooden item itself acts as the substrate of the tag.

Brush-painting has been previously successfully used for fabrication of tag antennas on fabric substrate with silver nanoparticle ink [15], and on wood substrate with silver and copper nanoparticle inks [16]. In this study, cost-effective screen printable silver ink (Metalon HPS-021LV silver flake ink [17]) was used. The tag antennas were brush-painted through a stencil (50 μm thick polyimide film) on plywood substrate, by using only one layer of ink. A tag antenna showed in Figure 1(a) was utilized as the antenna geometry. The wood substrate, presented in Figure 1(b), used in this study was 4 mm thick birch plywood.

Efficient and low-cost manufacturing is more and more important, as a huge amount of RFID components is needed for future IoT applications. These requirements mean that the long sintering times needed in heat sintering are not acceptable. Flash lamp sintering is a photonic sintering method that in ambient conditions uses very short light pulses to heat the ink to a high enough temperature within few micro- or milliseconds. Such transient heating minimizes the damage to heat sensitive substrates. Photonic sintering reduces the sintering times significantly, compared to the widely used heat sintering, which can take tens of minutes. The photonic sintering in this study was done using Xenon Sinteron 2010-L system. The sintering system parameters are lamp voltage, flash pulse duration, and number of flash pulses. The lamp voltage can be adjusted between 1800 V and 3000 V, in 50 V increments. The pulse duration can be adjusted and the time between pulses can also be chosen. In order to find the optimized sintering parameters, the resistances of fabricated antennas were measured after sintering, using Fluke 111 True RMS multimeter, and by placing the measurement probes on the corners of the antenna pattern (Diagonal 1: upper left and lower right corners, Diagonal 2: upper right and lower left

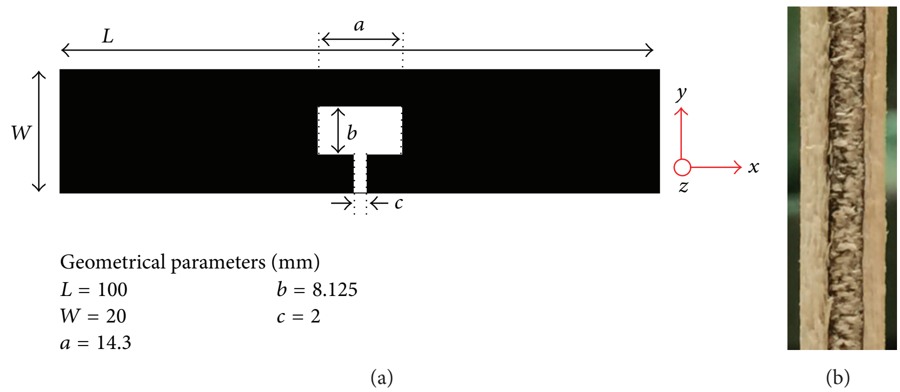


Figure 1: Studied tag antenna geometry (a) and cross section of the used plywood material (b).

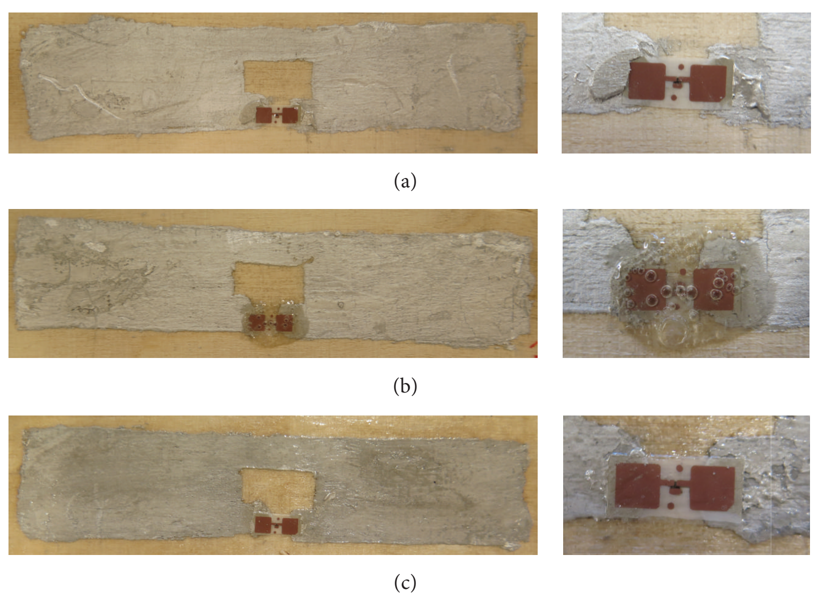


Figure 2: Noncoated tag and a close-up of the IC-area (a), IC-coated tag and a close-up of the IC-area (b), and all-coated tag and a close-up of the IC-area (c).

Table 1: Sintering parameters and measured resistances for antennas on plywood.

Voltage (V)	Time (μs)	Diagonal 1 (Ω)	Diagonal 2 (Ω)
2500	2500×2	5.8	5.3
2500	3000×2	4.2	3.9
3000	3000×2	2.3	2.8

corners). The used sintering parameters and the measured resistances for the best three photonically sintered antennas can be seen in Table 1. Based on this preliminary study, the chosen sintering parameters were 3000 V and 3000 μs, with two flash pulses.

The tag IC utilized in this experiment was NXP UCODE G2iL series IC [14], which has a low wake-up power of 15.8 μW (−18 dBm). The manufacturer had mounted the chip on a fixture with two $3 \times 3\,\text{mm}^2$ copper pads, which we connected to the antenna terminals using conductive epoxy (Circuit Works CW2400).

In order to achieve reliable and durable sensor tags against various environmental conditions, but still enabling their efficient use as sensors, the shielding of the IC and the antenna needs to be considered. Thus, finally, regular waterproof glue (Gutermann Creativ HT2) was brush-painted as a protective coating over tag antennas and ICs. We used samples where (a) only the IC-area was coated and (b) the whole tag was coated with the glue. For comparison purposes we used tags with no coating on the IC or on the antenna. Photos of the fabricated sensor components can be seen in Figures 2(a), 2(b), and 2(c).

4. Testing the Possibilities of Passive Wireless Humidity Sensors on Plywood Substrate

In order to examine the possibilities to integrate these passive sensors into wooden structures, the brush-painted tags on plywood substrate were tested for moisture absorption and wireless performance. The tags' wireless performance was

Table 2: Results of moisture absorption: mean change in mass and standard deviation after each testing time.

	Time	After 100% RH Δm (%) mean	After 100% RH Δm (%) st. dev.	After 9 days Δm (%) mean	After 9 days Δm (%) st. dev.
Noncoated	5 min	20.51	0	0.39	0
	1 h	46.08	0	0.44	0
IC-coated	5 min	22.66	0.08	0.46	0.03
	1 h	37.56	1.74	0.47	0.13
All-coated	5 min	14.90	6.60	0.19	0.13
	1 h	31.22	5.92	0.47	0.05

tested before and after humidity exposure, after 9 days from humidity exposure, and finally behind and under wood layer.

4.1. Measurements of Moisture Absorption. The moisture absorption test measured the moisture absorption in 100% relative humidity (RH). Before testing, the samples were kept in office conditions for 9 days and then weighted. The testing times were 5 minutes and 1 hour (also shown in Table 2). During testing, noncoated tags, tags with a coated IC, and all-coated tags were weighed after each submission time, and the mean change in weight was calculated. All samples were measured again after drying 9 days in office conditions. The accuracy of weight measurement was 0.0001 g and 15 samples were measured.

4.2. Wireless Performance before and after Moisture Absorption. The performance of the brush-painted sensor tags was analyzed after tag manufacturing, after coating, and twice after the moisture absorption test: immediately after the 100% RH test and after 9 days in office conditions. The measurements were based on the measured threshold power (P_{th}), which is the minimum output power of an RFID reader to activate the tag under test from a given distance. It can be measured using RFID readers and testers with adjustable output power. In this work, we have used Voyantic Tagformance measurement system [18] to conduct the measurement through a range of frequencies from 800 MHz to 1000 MHz. Because the measured threshold power depends on the measurement site and hardware, we used the attainable free-space read range of the tag (d_{tag}) derived from P_{th} to provide universal tag characterization. As detailed in [19], we can estimate d_{tag} based on the measured threshold power of the tag under test and a system reference tag as

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{\text{EIRP}}{\Lambda}\frac{P_{th^*}}{P_{th}}}, \quad (1)$$

where Λ is a parameter (unit: watts) describing the sensitivity of the reference tag of the measurement system and P_{th^*} is the measured threshold power of the reference tag. In this paper, we report all the read range results under the European RFID emission regulation: EIRP = 3.28 W, in the direction of the positive y-axis in Figure 1. In general, the yz-plane is the omnidirectional plane of the dipole antenna where the read range is approximately equal in all directions. In all measurements, the tag was aligned for polarization matching with a linearly polarized reader antenna. Based on the calibration data provided by the manufacturer of the measurement system, we have estimated that the maximum variability in d_{tag} due to variability in the system reference tag (Λ) and the output power meter of the reader (P_{th} and P_{th^*}) is less than 5% throughout the studied frequency range.

The response from the passive tag is affected by the prevailing circumstances and surrounding materials. In case of a passive humidity sensor tag on plywood, the response of the tag as a function of increased humidity is measured. The increased moisture will change the permittivity of the wooden substrate and thus change the impedance of the antenna, which will create a mismatch between the tag antenna and the IC. The increased moisture will also increase the losses in the wooden substrate, degrading the overall tag performance. That is, the humidity will cause a degradation of the tag performance, enabling the antenna-based sensing of humidity.

5. Results

5.1. Results of Moisture Absorption in 100% RH. The results of the moisture absorption measurements can be seen in Table 2. According to these results, the mean change in mass was between 15% (all-coated) and 23% (IC-coated) already after 5 minutes in 100% RH, which means that the plywood material quickly absorbs a lot of moisture. After 1 h in 100% RH, the mean change in mass was between 31% (all-coated) and 46% (noncoated), which means that about half of the mass increase occurs during the first 5 minutes, and the degree of moisture saturation is most probably near 100% after 1 h. However, even though the plywood absorbs quickly a lot of moisture, it also dries after removal from moist conditions. In the mass measurements after 9 days, it can be seen that only a very small amount of moisture is still absorbed. These changes in mass after 9 days, compared to the initial measurements, are so small that they could also be due to changes in the moisture content of office conditions. The next step of this research is to conduct exact moisture level measurements that will be used in addition to these prototype stage moisture absorption measurements.

5.2. Results of Wireless Measurements. The read range results for noncoated, IC-coated, and all-coated tags (after 9 days in office conditions, after adding the possible protective coating,

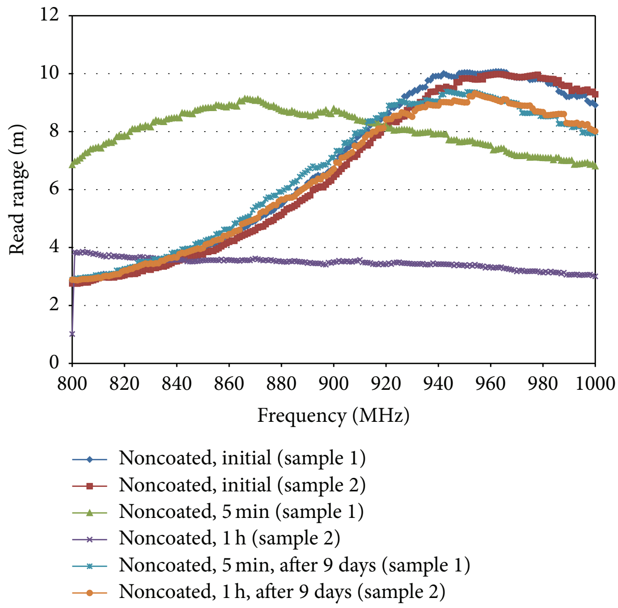


FIGURE 3: Measurement results for noncoated sensor tags.

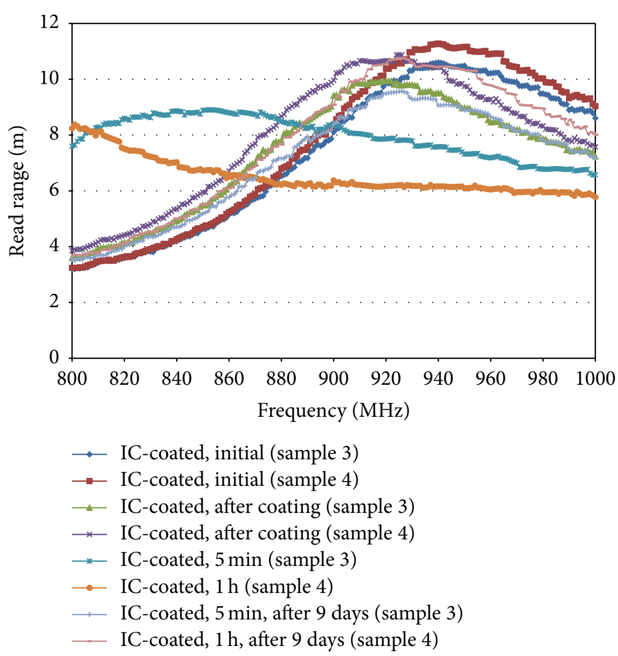


FIGURE 4: Measurement results for IC-coated sensor tags.

immediately after 100% RH testing, and after 9 days in office conditions) are shown in Figures 3–5, respectively.

As shown, these tags initially achieved peak read ranges of 10-11 meters in 940–970 MHz, which is more than sufficient for embedded humidity sensor applications. The achieved results are in line with the earlier results realized with the same antenna geometry: in [3], brush-painted silver nanoparticle RFID tags with the same antenna geometry on polyimide substrate showed peak read ranges of over 9 meters in the frequency range of 940–970 MHz (with photonic sintering)

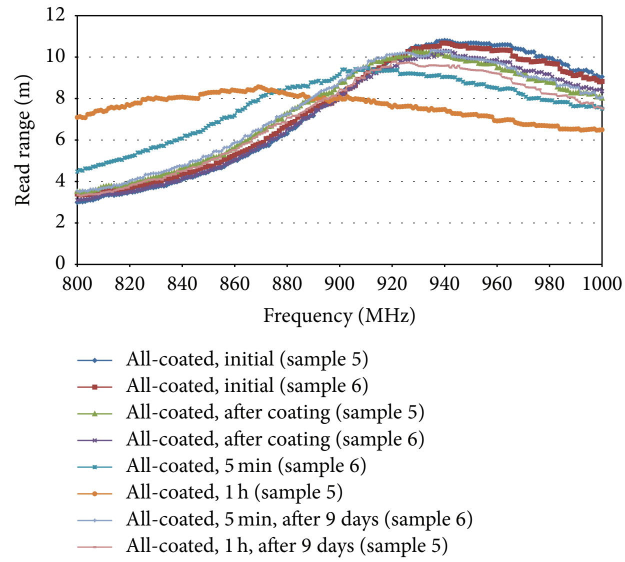


FIGURE 5: Measurement results for all-coated sensor tags.

and over 8 meters in the frequency range of 940–970 MHz (with heat sintering). Also, in [16], read ranges of about 5 and 3 meters throughout the global UHF RFID band were measured for brush-painted silver and copper nanoparticle RFID tags, respectively, with the same antenna geometry on wood substrate. For these tags, there was no clear peak read range at any frequency. A wooden surface was found to be a challenging surface for brush-painted nanoparticle, inkjet-printable inks, due to its porosity and high surface roughness, as the ink droplets were easily absorbed by the substrate [16]. This problem can be avoided by using screen printing inks, such as the ink in this study. However, if antenna geometries with really narrow and precise conductors are needed, use of inkjet-printable nanoparticle inks as sensor antenna could be studied with an additional substrate material on top of the plywood.

The measurement results presented in Figures 3–5 show that after being exposed to 100% RH, the performance of the tags changed significantly. The most dramatic change can be seen in Figure 3 for the noncoated tags. The maximum read range decreased from about 10 meters to below 4 meters, and no peak in read range in any frequency could be seen. The read ranges of the noncoated tags changed immediately after 5 minutes exposure to 100% RH, as can be seen in Figure 3, but the change was not as radical as after 1-hour exposure time. After 9 days in office conditions, the performance of the tags returned back to normal, as the tags had dried. These results of wireless read range measurement are supported by the earlier mass change measurement results.

The 100% RH exposure also affected the read ranges of the IC-coated tags after 5 minutes of humidity exposure, and even more after 1 hour in 100% RH. The performance of the IC-coated tags is very similar to the noncoated tags. After 1 hour in high humidity, the performance of the IC-coated tags seems to be better than the noncoated tags, which is probably due to the effects of moisture on the noncoated IC in case of the noncoated tags. The all-coated tags endured 100% RH exposure quite well: after 1 hour in 100% RH, the peak read range was 3 meters shorter than before any humidity testing. However, the peak frequency changed to significantly lower frequency. Altogether, the all-coating of tags shields the tags very well against 100% RH, and the reliability of the tags in normal RFID identification applications can be significantly increased by coating. After 9 days in office conditions, also the performance of the IC-coated and all-coated tags returned back to normal, whose results are also supported by the mass change measurement results.

In measurements of the IC-coated and all-coated tags, it could be seen that the coating of the IC-area affects the read range up to some extent. The peak read ranges of these tags were slightly shorter after coating than before coating. This change is in the range of about 1 meter and thus acceptable. The read ranges are more than sufficient to the intended applications even after the coating process.

According to our results, the moisture content of the substrate affected the passive UHF RFID tag performance on plywood substrate. The moisture did not prevent the tags from working, although the tag antenna impedance and the ohmic losses were affected by the moisture. These first results are very encouraging to further investigate the moisture sensing based on brush-painted passive UHF RFID tags on plywood substrate. The relation of the humidity exposure time and the change in the read range, especially in case of the noncoated tags, indicate that the tags could be used as humidity sensors in addition to normal RFID identification purposes. If the tags are intended to be used only as normal RFID identification tags in a high humidity environment, the all-coated tag should be chosen, because of the remarkable reliability increase against humidity. Based on our results, adding the protective coating on only the IC-area does not give any significant benefit either in use as a humidity sensor or in normal use as an identification tag: the reliability of the all-coated tags is significantly better and the sensor sensitivity to humidity is greater without any coating. However, a longer-term exposure to high humidity must first be studied.

Next, the tags were measured behind a 4 cm thick wooden wall and under a 4 cm thick wooden layer, and the measurement results can be seen in Figures 6 and 7, respectively. Based on our measurements, the wooden material on top of the tag or in front of the tag had a decreasing effect on the read range, and the peak frequency changed to lower frequency. In addition, the peak frequency is not as clear as without a wood layer. However, all tags still achieved read ranges of 6–9 meters throughout the global UHF RFID band. According to these results, the fabricated tags are suitable to be embedded into various wooden products and into wooden structures. It should be noted, however, that all of the measurements were performed in situations where there were no adjacent tags in close proximity. In practical applications, several tags may lay in close proximity. As tags are brought closer to one another, their operation characteristics can alter significantly [20, 21]. If the mutual coupling effect is not taken into account when placing the embedded tags, the readability of the tags could be degraded.

As copper-based conductive inks have recently provided more cost-effective alternatives to commonly used silver inks, the next step in our research will be to study the use of copper-based tag components as humidity sensors. The first prototype copper tag on plywood substrate was fabricated from Metalon ICI-021 copper oxide ink [22], by using brush-painting and photonic sintering. The read range measurement results are shown in Figure 8 and the fabricated tag is

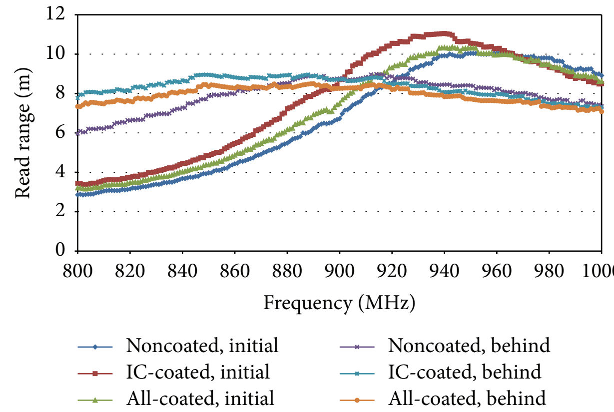


Figure 6: Measurement results behind 4 cm thick wooden wall.

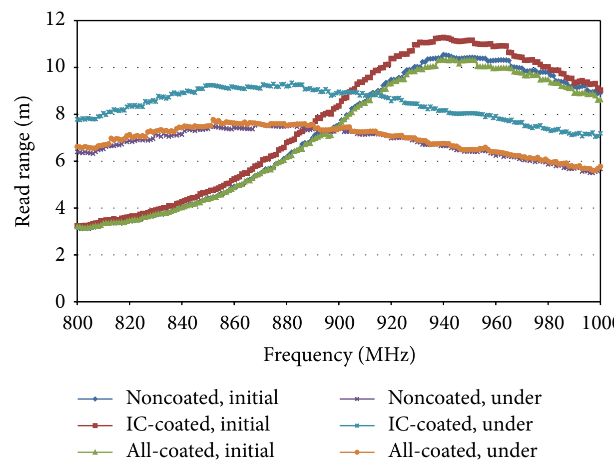


Figure 7: Measurement results under 4 cm thick wooden layer.

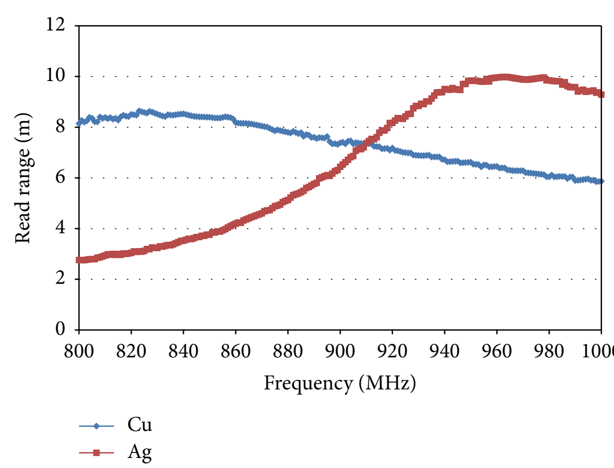


Figure 8: Measurement results for copper and silver tags.

Figure 9: Fabricated copper tag.

presented in Figure 9. According to our measurement results, the copper tags achieved peak ranges of about 8 meters, and read ranges of over 6 meters throughout the global UHF RFID band. Thus, these copper tags on a wood substrate provide a great potential for future wireless applications. The next step is to study their use as humidity sensors.

6. Conclusions

In this paper, embedding of fully passive RFID-based humidity sensors into plywood structures was studied. The sensor tag antennas were brush-painted on plywood substrate with silver ink and photonic sintering was used as the sintering method. These fabrication methods enable fast and cost-effective manufacturing of sensor tags. The sensor performance was strongly dependent on the amount of moisture the tags were exposed to. According to our results, the fabricated RFID-based humidity sensor components have a great potential to be utilized in humidity sensing applications but also in automatic identification and supply chain control of various wooden products, especially in the packaging and construction industry. To the best of our knowledge, this is the first demonstration of brush-painted humidity sensor tags. In the next stage, the sensors will be optimized for the readout with an off-the-shelf RFID reader operating in a fixed regionally regulated frequency band. Also the use of more cost-effective copper-based inks will be further studied.

Conflict of Interests

None of the authors has any conflict of interests.

References

[1] M. M. Tentzeris, L. Yang, A. Rida, A. Traille, R. Vyas, and T. Wu, "Inkjet-printed RFID tags on paper-based substrates for UHF 'cognitive intelligence' applications," in *Proceedings of the 18th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '07)*, pp. 1–4, IEEE, Athens, Ga, USA, September 2007.

[2] J. Virtanen, J. Virkki, L. Sydänheimo, M. Tentzeris, and L. Ukkonen, "Automated identification of plywood using embedded inkjet-printed passive UHF RFID tags," *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 3, pp. 796–806, 2013.

[3] E. Sipilä, J. Virkki, L. Sydänheimo, and L. Ukkonen, "Effect of sintering method on the read range of brush-painted silver nanoparticle UHF RFID tags on wood and polyimide substrates," in *Proceedings of the IEEE RFID Technology and Applications Conference (RFID-TA '14)*, pp. 219–222, Tampere, Finland, September 2014.

[4] P. V. Nikitin and K. V. S. Rao, "Antennas and propagation in UHF RFID systems," in *Proceedings of the IEEE International Conference on RFID*, pp. 277–288, IEEE, Las Vegas, Nev, USA, April 2008.

[5] D. Dobkin, *The RF in RFID: Passive UHF RFID in Practice*, Newnes, Elsevier, 2008.

[6] G. Marrocco, "Pervasive electromagnetics: sensing paradigms by passive RFID technology," *IEEE Wireless Communications*, vol. 17, no. 6, pp. 10–17, 2010.

[7] F. Long, X. D. Zhang, T. Björninen et al., "Implementation and wireless readout of passive UHF RFID strain sensor tags based on electro-textile antennas," in *Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP '15)*, pp. 1–5, IEEE, Lisbon, Portugal, April 2015.

[8] J. Virtanen, L. Ukkonen, T. Björninen, and L. Sydänheimo, "Printed humidity sensor for passive UHF RFID systems," in *Proceedings of the IEEE Sensors Applications Symposium (SAS '10)*, pp. 269–272, Limerick, Ireland, February 2010.

[9] S. Merilampi, T. Björninen, L. Ukkonen, P. Ruuskanen, and L. Sydänheimo, "Embedded wireless strain sensors based on printed RFID tag," *Sensor Review*, vol. 31, no. 1, pp. 32–40, 2011.

[10] K. Chang, Y. H. Kim, Y. J. Kim, and Y. J. Yoon, "Functional antenna integrated with relative humidity sensor using synthesised polyimide for passive RFID sensing," *Electronics Letters*, vol. 43, no. 5, pp. 7–8, 2007.

[11] A. Oprea, N. Bârsan, U. Weimar, M.-L. Bauersfeld, D. Ebling, and J. Wöllenstein, "Capacitive humidity sensors on flexible RFID labels," *Sensors and Actuators B: Chemical*, vol. 132, no. 2, pp. 404–410, 2008.

[12] Y. Jia, M. Heiss, Q. Fu, and N. A. Gay, "A prototype RFID humidity sensor for built environment monitoring," in *Proceedings of the International Workshop on Education Technology and Training and the International Workshop on Geoscience and Remote Sensing (ETT-GRS '08)*, vol. 2, pp. 496–499, IEEE, Shanghai, China, December 2008.

[13] Forest Products Laboratory, "Wood handbook—wood as an engineering material," General Technical Report FPL-GTR-113, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wis, USA, 2001.

[14] NXP UCODE G2iL IC, June 2015, http://www.nxp.com/documents/data_sheet/SL3S1203_1213.pdf.

[15] J. Virkki, T. Björninen, L. Sydänheimo, and L. Ukkonen, "Brush-painted silver nanoparticle UHF RFID tags on fabric substrates," in *Proceedings of the Progress in Electromagnetics Research Symposium (PIERS '14)*, pp. 2106–2110, Guangzhou, China, August 2014.

[16] E. Sipilä, J. Virkki, L. Sydänheimo, and L. Ukkonen, "Experimental study on brush-painted metallic nanoparticle UHF RFID tags on wood substrates," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 301–304, 2015.

[17] Metalon HPS-021LV Silver Screen Ink, May 2015, http://store.novacentrix.com/v/vspfiles/assets/images/metalon%20hps-021lv_2230.1.pdf.

[18] Voyantic, Espoo, Finland, May 2015, http://www.voyantic.com/.

[19] J. Virkki, T. Björninen, S. Merilampi, L. Sydänheimo, and L. Ukkonen, "The effects of recurrent stretching on the performance of electro-textile and screen-printed ultra-high-frequency radio-frequency identification tags," *Textile Research Journal*, vol. 85, no. 3, pp. 294–301, 2015.

[20] H.-J. Li, H.-H. Lin, and H.-H. Wu, "Effect of antenna mutual coupling on the UHF passive RFID tag detection," in *Proceedings of the IEEE International Symposium on Antennas and*

Propagation and USNC/URSI National Radio Science Meeting (APSURSI '08), San Diego, Calif, USA, July 2008.

[21] F. Lu, X. Chen, and T. T. Ye, "Performance analysis of stacked RFID tags," in *Proceedings of the IEEE International Conference on RFID*, pp. 330–337, IEEE, Orlando, Fla, USA, April 2009.

[22] Metalon ICI-021 Copper Oxide Screen Ink, May 2015, https://store.novacentrix.com/v/vspfiles/assets/images/metalon%20ici-021%202229.1.pdf.

PUBLICATION V

Parametric Optimization of Inkjet Printing and Optical Sintering of Nanoparticle Inks

Erja Sipilä[1], Yanan Ren[1], Johanna Virkki[1], Lauri Sydänheimo[1], Manos M. Tentzeris[2], and Leena Ukkonen[1]
[1]Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere, Finland
[2]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, USA

***Abstract*—In this paper, the parameters for inkjet-printing and photonic sintering of silver and copper nanoparticle inks on flexible polyimide substrate were studied by manufacturing simple line patterns. The results were then utilized to manufacture passive ultra high frequency (UHF) radio frequency identification (RFID) tag antennas on polyimide substrate. The tag's performance was evaluated by wireless measurements. Tags achieved peak read ranges of 3.6-5.5 meters, which can be considered suitable for practical applications.**

***Index Terms*—inkjet printing, photonic sintering, RFID, UHF, tag, antenna, nanoparticle ink.**

I. Introduction

Passive ultra high frequency (UHF) radio frequency identification (RFID) tags are seen as the key enablers of the Internet of Things (IOT), a conceptual vision to connect people, things and devices and create a ubiquitous computing world. In order to connect everyday objects to large networks, this kind of simple, reliable, and cost-effective technology is crucial.

Currently the most commonly used method for fabricating RFID tag antennas in mass production is etching. Besides for etching being a subtractive method, it needs lots of environmentally harmful chemicals. Thus, the use of additive manufacturing methods, such as printable electronics, is a growing trend. In additive manufacturing, the materials are added only to locations where they are needed, thus significantly decreasing waste compared to traditional manufacturing methods. Great potential lies, e.g., in use of wood, fabric, and flexible materials, such as polyimide, as a substrate for RFID components. Inkjet printing can also allow tags to be printed directly onto product packages. These RFID components can be used, e.g., in intelligent transportation, logistics, and healthcare applications.

Inkjet printing of RFID tags using silver nanoparticle ink and heat sintering has been successfully studied, e.g., in [1-3]. The main limitations of this method are the high cost of silver nanoparticle ink and the long heat sintering time. Especially the long sintering time prevents the use of this manufacturing technology in mass production.

The substrate material plays a big role in additive RFID tag manufacturing. Different substrate materials need different printing parameters, because they have different surface properties and morphologies. In addition, the substrate material has to withstand the sintering process, e.g., high temperature in heat sintering. Naturally, the substrate material should be cost-effective and preferably also flexible.

For RFID technology to spread to new application areas in the IOT, the manufacturing methods and materials for RFID tag antenna manufacturing have to be optimized. This also means that effective and optimized sintering methods are needed. Flash lamp sintering is a photonic sintering method that in ambient conditions uses short light pulses from a flash lamp to heat the ink to a high enough temperature within milliseconds. Such transient heating minimizes the damage to sensitive substrates [4] and enables roll-to-roll mass production. In addition, it allows cheaper ink alternatives, e.g., copper nanoparticle ink, to be used, because the sintering method reduces significantly the problem of non-conductive copper oxide formation.

In this study, to efficiently manufacture inkjet-printed passive UHF RFID tag antennas, we first optimized the manufacturing parameters for inkjet printing and photonic sintering of silver and copper nanoparticle inks on polyimide substrate. The optimized manufacturing parameters were used to fabricate prototype UHF RFID tags and the tags were evaluated by wireless measurements.

II. Photonic Sintering

Manufacture of inkjet-printed conductive structures consists of two steps: inkjet-printing of the desired pattern with nanoparticle ink and metallization of it by sintering. Several different sintering techniques are available, such as laser, microwave, plasma, and electrical sintering, as well as sintering by chemical agents. Each solution naturally comes with different restrictions and shortcomings. In case of copper inks, heat sintering is not easy because of non-conductive copper oxide; a copper ink needs an inert atmosphere or an alternative approach to sintering. Thus, the best alternative to thermal sintering process is an active research area [5]. Perhaps the most promising method, especially when considering low-cost mass-production, is the photonic sintering method with a Xenon flash lamp.

The idea in photonic sintering is to transfer energy via light radiation to conductive particles so fast, within micro- or milliseconds, that the conductive particles heat enough to sinter before they transfer too much of heat energy to the substrate [6]. In addition, the very short sintering time prevents oxidation of copper nanoparticles during photonic sintering process [4].

In this study, the inkjet-printed patterns were sintered using Xenon Sinteron 2010-L system [7], which is presented in Fig.1. The sintering system parameters are lamp voltage, pulse duration, and flash number (single, double, continuous or burst). The lamp voltage can be adjusted between 1800 V and 3000 V, in 50 V increments. The pulse duration can be adjusted (min 100 µs, max 2000 µs), as can the time period (the time period includes the pulse and the time between the pulses). The minimum time period is 100 ms and maximum is 5000 ms. In burst mode, the sintering system will count the flashes, and the count number can be adjusted (min 1, max 2000). In addition, there are two plates that can be used to shape the light into a stripe that hits the sample. This aperture spacing can be adjusted from 10 mm to 80 mm. In this study, the spacing was set to 20 mm. This is normally enough for UHF RFID antennas, as the whole antenna can be sintered at once.

Fig. 1. Xenon Sinteron 2010-L photonic sintering system.

III. MANUFACTURING OF UHF RFID TAGS

The parameters for both manufacturing steps, inkjet printing and sintering, need to be optimized to produce homogenous and highly conductive structures to form high quality antennas. The optimization of these parameters is strictly case-related, depending on the chosen ink and substrate material, as well as the inkjet printing and sintering equipment.

In this study, both silver and copper nanoparticle inks were studied. We used Harima NPS-JL silver nanoparticle ink (with particle sizes of 5-12 nm and a maximum achievable resistivity of 4-6 µΩ·cm) and ANI Cu-IJ70 copper nanoparticle ink (with particle sizes of 10-200 nm and a maximum achievable resistivity of 5-7 µΩ·cm) [8, 9]. They were inkjet-printed onto 50 µm thick polyimide (PI) substrate (Dupont™ Kapton®) with Fujifilm Dimatix DMP-2831 inkjet printer, equipped with 10□pl print head nozzles. Kapton is a low-loss PI film, which provides a smooth, heat-resistant surface for high precision inkjet printing. Thus, it is optimal to be used in this study.

For the chosen substrate material, the printing quality was affected by the temperature of the ink cartridge and the platen, jetting voltage and jetting frequency, as well as the pattern resolution. Among these parameters, pattern resolution is the most crucial one. To ensure that the ink droplets jetted to the polyimide substrate attach well on the substrate surface, without unnecessary spreading, we did preliminary test on droplets. A microscope image of silver nanoparticle ink droplets is shown as an example in Fig. 2; the droplet diameter of silver ink on PI was about 86 µm, so we chose 635 dpi as the resolution, meaning the drop spacing is approximately the radius of the droplet, 40 µm. Similar preliminary study was done for the inkjet printing parameters of the copper ink. The platen temperature was chosen quite high in the equipment, 56 °C (60 °C is the maximum). A high temperature helps ink to form a uniform surface and to dry faster. Based on the results of our preliminary tests, the actual printing parameters were chosen to be the ones listed in TABLE I. The thickness of the ink layer depends on the printing direction line width of the conductor, and, therefore, thickness varies significantly in a given sample in different areas, as presented in [10].

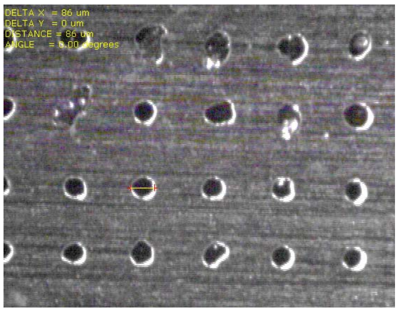


Fig. 2. Drop size test of silver nanoparticle ink on PI, droplet diameter is about 86 µm.

After finding the inkjet printing parameters, the parameters for photonic sintering were studied. The lamp voltage was changed from 1800 V to 3000 V, with a step of 50 V, while the pulse width was fixed to 2000 µs, which is the maximum allowed duration in equipment specifications. Also the number of needed flash pulses was studied; we did preliminary tests with 1, 2, 5, 10 and 20 pulses. The sintering results were primarily evaluated by sheet resistance measurements of inkjet-printed simple 5 mm x 50 mm line patterns (see Fig. 3).

The silver ink line pattern became fully sintered with a lamp voltage of 3000 V and two flash pulses were needed. Lower energy resulted as higher resistance while higher energy (more flash pulses) did not reduce the resistance. Photonic sintering of the copper ink was significantly more challenging than photonic sintering of the silver ink. The copper ink was successfully sintered with a single flash pulse of 2500 V. The printed trace was partially sintered when the lamp voltage was lower and the surface became more uneven when sintered with a higher voltage.

After inkjet printing and photonic sintering of these line patterns, we measured their resistances using Fluke 111 True RMS multimeter. The resistances were measured by placing the measurement probes on the opposite corners of the line pattern. The resistances are presented in TABLE II. Based on these results, as well as based on the results achieved in [3, 10], we chose to use three layers of ink in both cases. One layer was not enough, especially with silver nanoparticle ink. The inks had different structures and this is probably causing the differences in the resistance measurement results of one-layer structures. Microscope images of three-layer sample surfaces after photonic sintering are shown in Fig. 4.

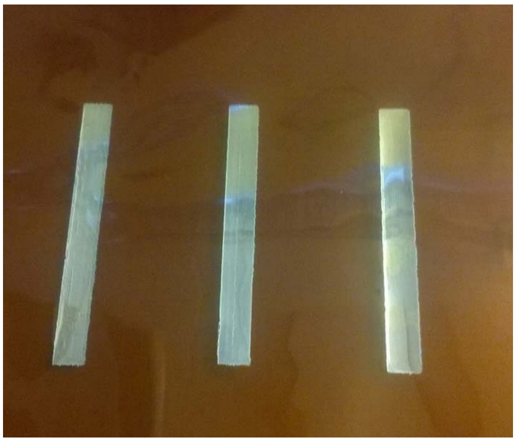


Fig. 3. Silver nanoparticle ink line patterns on PI for parameter optimization.

TABLE I. OPTIMIZED INKJET PRINTING PARAMETERS

	Silver ink	Copper ink
Cartridge temperature (˚C)	28	28
Platen temperature (˚C)	56	56
Jetting voltage (V)	28	25
Jetting frequency (kHz)	23	23
Pattern resolution (dpi)	635	726

TABLE II. RESISTANCES OF MANUFACTURED LINE PATTERNS

Ink	Number of ink layer(s)	Substrate	Resistance (Ω)
Silver	1	PI	2
Silver	3	PI	0,8
Copper	1	PI	1,6
Copper	3	PI	1

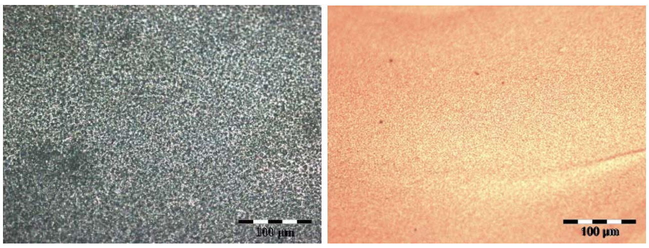


Fig. 4. Optical microscope images of manufactured three-layer silver (left) and copper (right) samples.

After finding the optimal parameters for manufacturing, we manufactured the prototype UHF RFID tags antennas. The UHF RFID tag antenna geometry applied in this study is shown with a manufactured prototype tag in Fig. 5. This geometry represents a typical dipole antenna layout for passive UHF RFID tags and it has been already successfully used in [10]. Three-layer tag antennas were inkjet printed with silver and copper nanoparticle inks on polyimide substrate with the optimized printing parameters. The antennas were sintered using optimized photonic sintering parameters. The tag IC used in this study is NXP UCODE G2iL series IC [11]. The manufacturer had mounted the IC on a strap. The strap was attached to each tag antenna with conductive silver epoxy resin to form a fully functional passive UHF RFID tag.

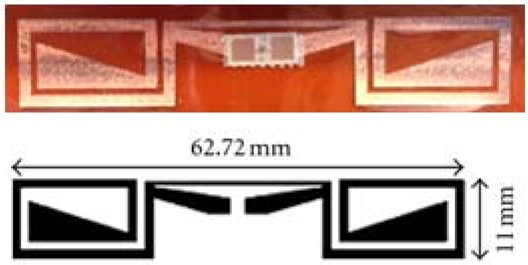


Fig. 5. Bottom: utilized tag antenna geometry. Top: a prototype of inkjet-printed and photonically sintered UHF RFID tag using copper nanoparticle ink.

IV. MEASUREMENTS

The prototype inkjet-printed UHF RFID tags were evaluated with Tagformance RFID measurement unit. The core operations are performed with a vector signal analyzer. Two key properties of passive UHF RFID tags were measured: threshold power and theoretical read range. Both quantities can be measured as a function of transmit frequency or as a function of tag to reader antenna angle at a point frequency. Threshold power describes the minimum transmit power, at the transmit port, to activate the tag and can be expressed as:

$$P_{TS} = \frac{P_{IC}}{G_{tx}G_{tag}\tau\left(\frac{\lambda}{4\pi d}\right)^2 \left|\hat{p_{tx}}\cdot\hat{p_{tag}}\right|^2} \quad (1)$$

where P_{IC} is the sensitivity of the RFID IC, G_{tx} and G_{tag} are the gains of the reader and tag antenna, τ is the power transmission coefficient, d is the distance between the tag and reader antenna, p_{tx} and p_{tag} the unit electric field vectors of the transmitting antenna and tag antenna. The inner product of the electric field vectors describes the power loss due to possibly mismatched polarization planes between the reader and tag antenna.

Theoretical read range describes the maximal distance between the tag and reader antenna in an environment without reflections or external disturbances. The Tagformance measurement system is able to calculate the theoretical read range of a tag using its measured threshold power along with the measured forward losses. The forward loss describes the link loss between the generator's output port to the input port of an equivalent isotropic antenna placed at the tag's location. The forward loss from the transmit port to the tag is calculated using a reference tag during the calibration procedure of Tagformance. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels and can be calculated as:

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}}, \quad (2)$$

where λ is the wavelength transmitted from the reader, *EIRP* is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, P_{TS} and L_{fwd} are the measured threshold power and forward losses correspondingly.

The theoretical read ranges for three-layer tags are shown in Fig. 6 and the threshold power results are shown in Fig. 7. The prototype three-layer silver tags reached peak read ranges of 5.5 meters and the three-layer copper tags showed peak read ranges of 3.6 meters. The read range results of these silver tags agree with those achieved in [10], where the same inkjet-printed silver tag antenna was fabricated, though with heat sintering.

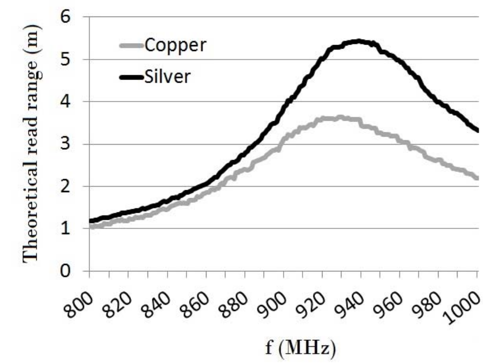


Fig. 6. Measured read ranges of inkjet-printed UHF RFID tags.

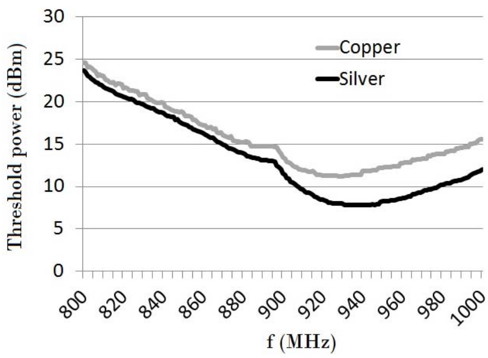


Fig. 7. Measured threshold powers of inkjet printed UHF RFID tags.

V. CONCLUSION

In this study, we manufactured UHF RFID tags with optimized inkjet-printing and photonic sintering parameters. First, we studied the optimal printing and sintering parameters for both silver and copper nanoparticle inks and then manufactured prototype UHF RFID tag antennas on flexible polyimide substrate. The achieved peak read range depends on the ink type and the number of printed layers. With three printed layers of silver nanoparticle ink and by efficient flash lamp sintering, read ranges of 5.5 meters were achieved. Even though the results are very promising, a lot of research work is still needed as each substrate needs its own optimized manufacturing parameters. Also, use of new ink materials, such as nickel nanoparticle ink, can provide even more possibilities for the UHF RFID technology. In addition, selective ink deposition could be used to significantly reduce the amount of conductive ink and time by identifying areas with high surface current densities and applying additional nanoparticle ink onto such areas.

REFERENCES

[1] L. Yang , A. Rida , R. Vyas, and M. M. Tentzeris, "RFID tag and RF structures on paper substrates using inkjet-printingtechnology", IEEE Trans. Microw. Theory Tech., vol. 55, no. 12, pp.2894 -2901, December 2007.

[2] J. Virkki, J. Virtanen, L. Sydanheimo, L. Ukkonen, and M. M. Tentzeris, "Embedding inkjet-printed antennas into plywood structures for identification and sensing", Proc. IEEE RFID-TA, pp.34-39, November 2012.

[3] J. Virtanen, T. Björninen, L. Ukkonen, K. Kaija, T. Joutsenoja, L. Sydänheimo, and A. Z. Elsherbeni, "The effect of conductor thickness in passive inkjet printed RFID tags," Proc. IEEE APSURSI, pp. 1–4, July 2010.

[4] H. S. Kim, S.R. Dhage, D.E. Shim, and H.T. Hahn, "Intense pulsed light sintering of copper nanoink for printed electronics," Applied Physics A, vol. 97, no. 4, pp. 791-798, August 2009.

[5] B. Polzinger, F. Schoen, V. Matic, J. Keck, H. Willeck, W. Eberhardt, and H. Kueck, "UV-sintering of inkjet-printed conductive silver tracks," Proc. IEEE NANO, pp. 201-204, August 2011.

[6] K. A. Schroder, S. C. McCool, and W. F. Furlan, "Broadcast photonic curing of metallic nanoparticle films", Proc. Nanotech, vol. 3, Chapter 2, pp.198 -201, 2006.

[7] Xenon Sinteron 2010-L. Installation and User Manual. Xenon Corporation, June 2013.

[8] Harima, NPS-JL Silver Nanoparticle Ink, NanoPaste Series, Metal Paste for Thin Film Formation, Datasheet, http://www.harima.co.jp/en/products/pdf/16-17e.pdf (13.8.2014)

[9] Applied Nanotech Holdings, Inc, Cu-IJ70 Copper nanoparticle Ink, http://www.appliednanotech.net/tech/conductive_ink_cu.php (19.8.2014)

[10] J. Virtanen, J. Virkki, A. Z. Elsherbeni, L. Sydänheimo, and L. Ukkonen, "A selective ink deposition method for the cost-performance optimization of Inkjet-Printed UHF RFID tag antennas", Int J Antennas Propag, vol. 2012, Article ID 801014, 9 pages, 2012.

[11] NXP UCODE G2iL IC Datasheet, http://www.nxp.com/documents/data_sheet/SL3S1203_1213.pdf (13.8.2014)

PUBLICATION VI

Experimental Study on Brush-Painted Metallic Nanoparticle UHF RFID Tags on Wood Substrates

Erja Sipilä, Johanna Virkki, Lauri Sydänheimo, *Member, IEEE*, Leena Ukkonen, *Member, IEEE*

***Abstract*—Due to an increasing interest to add functionality in various products, versatile electronics manufacturing methods are needed for numerous applications. In this study, UHF RFID tag antennas manufactured by brush-painting directly on wood veneer substrate were examined. Silver and copper nanoparticle inks were used in antenna manufacturing. According to our measurements, brush-painted silver and copper nanoparticle UHF RFID tags showed read ranges of 5 and 3 meters, respectively, even when embedded inside wood layers. These read ranges are sufficient for many applications, e.g., in construction and packaging industry, where wood is a common material. The novel manufacturing process, its applications, and the achieved tag performance results are presented in this letter.**

***Index Terms*—Inks, manufacturing processes, nanoparticles, RFID tags, UHF antennas.**

I. Introduction

EMBEDDING electronics as a part of everyday structures is a growing trend. This makes integration of electronics and wood an interesting new research area.

Wood industry needs automated identification systems, which will provide identification and tracking of wood products throughout their lifetime. Nowadays identification is mainly done manually by using various codes, which is prone to errors and misreads that could lead to delays or wastage. In addition, external code labels can be easily damaged or lost. Instead, passive ultra high frequency (UHF) radio frequency identification (RFID) is an effective wireless identification technology that can be embedded into variety of objects [1]. The information can be restored throughout the lifecycle from the factory to the end user. RFID tags have already been applied to wood logs for timber supply chain [2] and for plywood boards [3]. A comprehensive introduction to passive UHF RFID systems is provided in [4].

Moreover, wood is a potential substrate material for various electronic applications. Wood has a high ratio of strength to weight and a remarkable record for durability and performance as a structural material. Dry wood has good insulating properties against heat and electricity. In addition, wood can be treated with preservatives and fire retardants, and can be combined with almost any other material for both functional and aesthetic uses [5].

Printing methods are the most common additive methods applied in RFID antenna fabrication [6]. Prototype RFID tags have been printed on wood substrate by screen printing [7] and by inkjet printing [3], using silver particle inks and heat sintering. These tags have showed good performance on wood substrate but their manufacturing has required several printed layers [3,7], more than one printing-sintering rounds with different printing directions [3], and long sintering times in the oven (20-60 minutes) [3,7]. In addition, in case of copper inks, heat sintering is problematic because of non-conductive copper oxide. Several sintering techniques have been proposed to overcome these problems, each solution coming with own restrictions and shortcomings. Thus, the best alternative to thermal sintering process is an active research area [8].

In this letter, the use of wood veneer as a substrate for brush-painted silver and copper nanoparticle passive UHF RFID tags is examined. This study is not focusing on maximization of the tag performance but on the use of these tags in the wood industry and in different wooden products. By brush-painting the tag antennas directly on wood, we can manufacture very thin tags through eliminating the need for additional substrate material. This will also create material and cost savings, along with opportunities for novel applications. In addition, brushing the tag antennas directly on such environmental-friendly substrate can have a huge effect on the environment as these wooden materials can replace currently used environmentally problematic polymer materials.

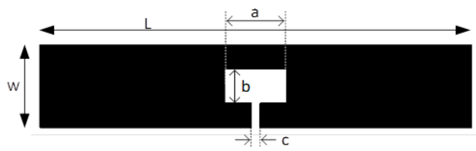
II. Fabrication of the Sample Tags on Wood Substrate

Brush-painting is simple and fast method, which enables mass production in the future. The manufacturing process involves only two process steps: painting and sintering, and antenna manufacturing is possible to do with only one brushed layer, which can offer great benefits in future RFID tag manufacturing. The brushing-method not only reduces process-steps, but also minimizes the need of conductive ink, because the ink is dispensed directly to the brush, and from the brush directly to the antenna area in the substrate.

This work was supported by the Academy of Finland, Emil Aaltonen Foundation and the Finnish Funding Agency for Technology and Innovation (TEKES).

All authors are with the Department of Electronics and Communications Engineering, Tampere University of Technology, Tampere 33720, Finland (e-mail: erja.sipila@tut.fi; johanna.virkki@tut.fi; lauri.sydanheimo@tut.fi; leena.ukkonen@tut.fi)

In our study, the tag antennas (See Fig. 1 for the dipole antenna geometry and Fig. 2 for the manufacturing process steps) were brush-painted through a stencil (stencil material was 50 µm thick PI film) on 1 mm thick wood veneer by using only one layer of ink. This antenna geometry was chosen because it is insensitive to edge roughness variations. The dielectric constant of wood veneer is 2.2 (at 0.8-1 GHz) and loss tangent is 0.1 (at 0.8-1 GHz). The used inks were Harima NPS-JL (Ag) [9] and ANI Cu-IJ70 (Cu) nanoparticle ink [10].



Geometrical parameters in millimeters.

L	W	a	b	c
100	20	14.3	8.125	2

Fig. 1. Antenna geometry.

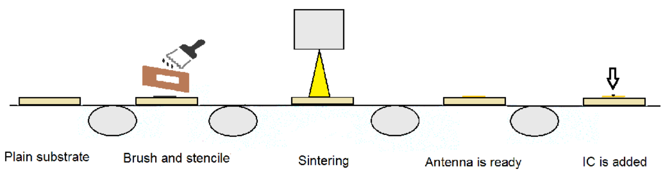


Fig. 2. Manufacturing steps.

After brushing the ink through the stencil, the tag antennas were sintered with a photonic sintering system that provides a high energy, pulsed light for reliable and efficient (extremely short processing time) sintering of conductive nanoparticles. The used sintering parameters can be seen in Table I. We used single flash pulse mode in both cases but in the case of the copper ink, it was used 3 times with a break of 1.5 seconds between the flashes. See Fig. 3 for the manufactured antennas.

TABLE I
SINTERING PARAMETERS

Parameter	Silver ink	Copper ink
Voltage (V)	3000	3000
Pulse time (us)	4000	4000
Pulse mode	single	single x 3

A wood veneer surface is challenging due to its porosity and high surface roughness. The ink is easily absorbed by the wood, preventing the nanoscale metallization particles of the ink to form a conductive layer. A unique characteristic of wood surfaces are their grain; the surface has valleys and hills that vary according to the grain (See Fig. 4 for microscope images). In the direction of the grain such variations are low, whereas against the grain variations are significant. In fact, in our previous study it was found out that RFID tag antennas inkjet-printed on wood veneer only in one direction did not function even with several layers of conductive ink, and that antennas which had the antenna geometry printed along the grain showed the best performance [3]. This was also discovered in our preliminary tests; the conductivity of the antenna brushed against the grain was significantly lower than conductivity of the antenna brushed along the grain. Therefore, the tag antennas should be brushed along the grain and the amount of used ink should be as small as possible. See Table II for the resistance measurement results in our preliminary tests. The resistance measurements were done using a Fluke 115 multimeter. The measurement probes were placed in the opposite corners of the brushed antenna. According to the results, it is clear that the resistances in copper antennas are higher than in silver antennas, which will later show as a difference in tag performance. The photonic sintering process with copper ink turned out to be more challenging than with silver ink, which may be caused by the oxidation of copper. Also, the sintering result with copper ink was not totally uniform throughout the whole antenna area.

TABLE II
ANTENNA RESISTANCES

Resistance	Silver ink	Copper ink
Antenna brushed along the grain (Ω)	2.2	3.8
Antenna brushed against the grain (Ω)	4.1	26

The tag IC utilized in this study is NXP UCODE G2iL series IC [11]. This chip has very high chip sensitivity (-18 dBm) which enables long read ranges. The IC-strap has an equivalent input parallel resistance and capacitance of 2.85 kΩ and 0.91 pF [12]. In addition, there is a T-match network in the antenna, witch matches the antenna impedance to the capacitive impedance of the IC.

The manufacturer had mounted the chip on a strap (copper on a plastic film). After sintering, we attached the pads of the strap to the antenna using a conductive silver epoxy resin. We did not concentrate on IC bonding process and the long-term reliability of the joint is thus not relevant in this study.

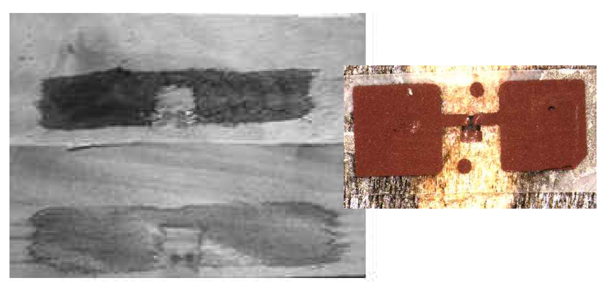


Fig. 3. Prototype RFID tags and a close-up of the tag IC.

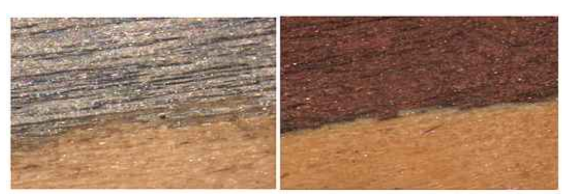


Fig. 4. Microscope images of silver ink (left) and copper ink (right) antennas, magnification x 12.5.

III. EVALUATION OF THE RFID TAG PERFORMANCE

All of the measurements made for this study were performed using a Tagformance RFID measurement unit [13]. The core operations of the measurement device are performed with a vector signal analyzer. Tagformance was used to measure the key properties of passive UHF RFID tags: threshold power, theoretical read range, and realized gain. All quantities can be measured as a function of transmit frequency or as a function of tag to reader antenna angle at a point frequency.

Threshold power describes the minimum transmit power, at the transmit port, to activate the tag. Threshold power of an arbitrary tag can be expressed as

$$P_{TS} = \frac{P_{IC}}{G_{tx}G_{tag}\tau\left(\frac{\lambda}{4\pi d}\right)^2\left|\hat{p}_{tx}\cdot\hat{p}_{tag}\right|^2}, \quad (1)$$

where P_{IC} is the sensitivity of the RFID IC, G_{tx} and G_{tag} are the gains of the reader and tag antenna, τ is the power transmission coefficient, d is the distance between the tag and reader antenna, p_{tx} and p_{tag} are the unit electric field vectors of the transmitting antenna and tag antenna. The inner product of the electric field vectors describes the power loss due to possibly mismatched polarization planes between the reader and tag antenna.

Theoretical read range describes the maximal distance between the tag and reader antenna in an environment without reflections or external disturbances. Tagformance measurement system is able to calculate the theoretical read range of a tag using its measured threshold power along with the measured forward losses. The forward loss describes the link loss between the generator's output port to the input port of an equivalent isotropic antenna placed at the tag's location. The forward loss from the transmit port to the tag is calculated using a reference tag during the calibration procedure of Tagformance. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels. Theoretical read range can be therefore calculated as

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}}, \quad (2)$$

where λ is the wavelength transmitted from the reader, *EIRP* is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, P_{TS} and L_{fwd} are the measured threshold power and forward losses correspondingly. The measured realized gain of the tag antenna is analyzed using the path loss measurement data from the measurement unit. Realized gain takes into account the antenna – IC impedance matching and can be calculated as

$$G_r = \frac{P_{IC,TS}}{L_{fwd}\cdot P_{TS}}, \quad (3)$$

where $P_{IC,TS}$ is the tag IC sensitivity, P_{TS} and L_{fwd} are as in equation (2).

The theoretical read range results were obtained from a fixed angle (the angle of the highest read range) between the reader antenna and the tag. The theoretical read ranges were measured for 4 silver and 4 copper nanoparticle ink tags. The results can be seen in Fig. 5. From these measured tags two well performing tags, Ag 2 and Cu 1 were chosen for other measurements.

The H-plane and E-plane realized gains were measured for tags Ag 2 and Cu 1 in free space at the European and USA center frequencies, 866.6 MHz and 915 MHz, respectively. These results can be seen in Fig. 6 and Fig. 7. Lastly, the theoretical read ranges were measured in potential real life situations; the tags Ag 2 and Cu 1 were embedded inside of 1 mm, 2 mm, and 2 cm layers of wood material. These results can be seen in Fig. 8.

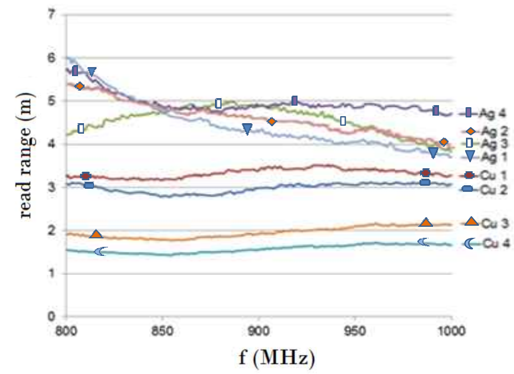


Fig. 5. Theoretical maximum read ranges at different frequencies.

In the measurements (see Fig. 5), maximum read ranges of about 4-5 and 1.5-3 meters through the global UHF RFID band were measured for the silver and copper nanoparticle tags, respectively. However, there is variance in results, especially in tag antennas made with copper nanoparticle ink. The variations can be, e.g., due to small differences in antenna geometry because of the ink spreading on wood substrate, due to variations in substrate material, knots that affect the ink absorption of the veneer, or due to the non-flat substrate (wood veneer was found to be be slightly curved), which affects the photonic sintering process. The sintering parameters are critical especially for the copper nanoparticle ink. With silver nanoparticle ink, there can be more variance in sintering parameters. Thus, the next step is to standardize the brush-painting process, especially the application and spreading of the ink on wood substrate, as well as the sintering process parameters.

In our previous study, inkjet-printed and heat-sintered silver nanoparticle UHF RFID tags on wood veneer, with quite similar tag antenna geometry, achieved peak read ranges of 6.5 meters and read ranges of over 2 meters throughout the global UHF RFID band [3]. Thus, these brush-painted antennas offer an alternative to inkjet-printed antennas on wood substrates. It should be noted, that the brushing method is not suitable for structures containing very small details; if very small dimension are required, inkjet printing is recommended. However, with basic geometries, it is possible to achieve suitable read ranges with only one brushed layer.

The embedded tags exhibit excellent robustness towards the amount of wood around them (Fig. 8). Adding thin layers of wood around the tags seems to even slightly improve the read ranges. Similar effect was found with inkjet-printed RFID tags in our previous study [3]. One possible reason is a changed impedance matching between the antenna and IC. Adding 2 cm of wood on both sides of the tag has a more significant effect on the read range; the read ranges of Ag and Cu tags shorten to 4 and 2 meters, respectively. However, these read ranges are still sufficient for many wireless applications.

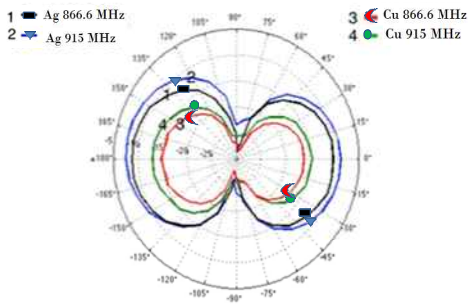


Fig. 6. E-plane realized gains at frequencies of 866.6 MHz and 915 MHz.

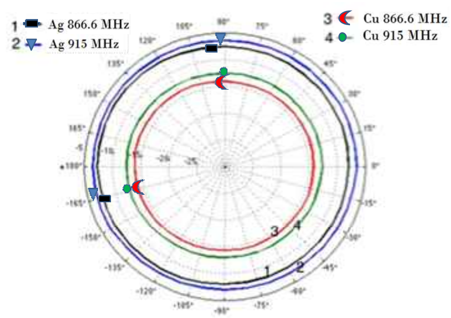


Fig. 7. H-plane realized gains at frequencies of 866.6 MHz and 915 MHz.

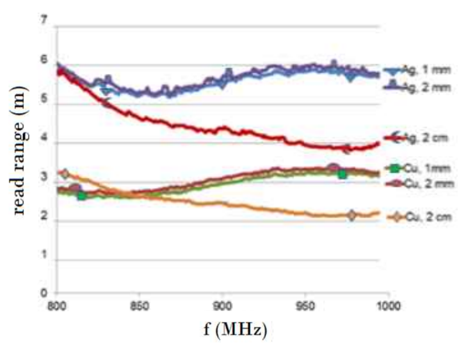


Fig. 8. Theoretical maximum read ranges at different frequencies when embedded inside 1mm, 2 mm, and 2 cm wood layers.

These results show that brush-painted passive UHF RFID tags have a great potential for future wireless applications. However, there are many things to consider in our future research. In the case of the wood substrate, the ink spread is the highest in the direction of the grain and the future tag antenna designs should be optimized so that there are no narrow gaps in the direction of the grain. Also, the brushing method needs to be optimized and a further analysis on the antenna surface structure is needed. Future work will also be the optimization of the amount of the ink as well as sintering times and parameters. Furthermore, the modelling of brush-painted antennas needs to be studied and optimized, because the uneven substrate surface together with grain orientation of the wood set extra challenges to mathematical models.

IV. Conclusion

Fabrication of antennas and electronics directly on different substrates, including wood and other renewable materials, is imperative for the development of future wireless platforms. We presented prototypes of passive UHF RFID tags with antennas brush-painted on wood substrate without any surface treatments, using only one layer of silver or copper nanoparticle ink, and sintered with photonic methods. According to their measured performance, these antennas offer a high potential for future wireless applications; maximum theoretical read ranges of about 5 and 3 meters through the global UHF RFID band were measured for the silver and copper nanoparticle RFID tags, respectively. However, a lot of work is still needed for the optimization and standardization of the novel manufacturing process.

References

[1] Welbourne, E., Battle, L., Cole, G., Gould, K., Rector, K., Raymer, S., Balazinska, M., Borriello, G., 2009. Building the Internet of Things Using RFID: The RFID Ecosystem Experience, Internet Computing, 13(3): 48-55.

[2] Korten, S. and Kaul, C., 2008. Application of RFID (Radio Frequency Identification) in the Timber Supply Chain, Croatian Journal of Forest Engineering, 29(9): 85-94.

[3] Virtanen, J., Virkki, J., Sydänheimo, L., Tentzeris, M. and Ukkonen, L. 2013. Automated Identification of Plywood Using Embedded Inkjet-printed Passive UHF RFID Tags, IEEE Transactions on Automation Science and Engineering, 10(3): 796-806.

[4] Dobkin, D., 2008. RF in RFID - Passive UHF RFID in Practice, Elsevier.

[5] Forest Products Laboratory, 2001. Wood Handbook — Wood as an Engineering Material, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[6] Merilampi, S., Björninen, T., Vuorimäki, A., Ukkonen, L., Ruuskanen, P. and Sydänheimo, L., 2010. The Effect of Conductive Ink Layer Thickness on the Functioning of Printed UHF RFID Antennas, IEEE special issue, RFID - a Unique Radio Innovation for the 21st Century, 98(9): 1610-1619.

[7] Virkki, J., Merilampi, S., Ukkonen, L., Sydänheimo, L., 2012. Performance of UHF RFID Tags Printed Directly on Plywood Structures, International Journal of RF Technologies: Research & Applications, 3(4): 283-302.

[8] Polzinger, B., Schoen, F., Matic, V., Keck, J., Willeck, H., Eberhardt, W. and Kueck, H., 2011. UV-sintering of Inkjet-printed Conductive Silver Tracks. In the Proceedings of the IEEE Conference on Nanotechnology.

[9] Harima, NPS-JL Silver Nanoparticle Ink, NanoPaste Series, Metal Paste for Thin Film Formation, Datasheet, http://www.harima.co.jp/en/products/pdf/16-17e.pdf (13.12.2013)

[10] Applied Nanotech Holdings, Inc, Cu-IJ70 Copper nanoparticle Ink, http://www.appliednanotech.net/tech/conductive_ink_cu.php (19.2.2014)

[11] NXP UCODE G2iL IC Datasheet, http://www.nxp.com/documents/data_sheet/SL3S1203_1213.pdf (13.2.2014)

[12] Björninen, T., Sydänheimo, L. and Ukkonen, L. 2012. Development and validation of an equivalent circuit model for UHF RFIC IC based on wireless tag measurements. In the Proceedings of the AMTA Symposium.

[13] Voyantic Tagformance RFID Measurement Unit, http://www.voyantic.com/tagformance (3.6.2014)

PUBLICATION VII

Effect of Sintering Method on the Read Range of Brush-painted Silver Nanoparticle UHF RFID Tags on Wood and Polyimide Substrates

Erja Sipilä, Johanna Virkki, Lauri Sydänheimo, Leena Ukkonen
Department of Electronics and Communications Engineering
Tampere University of Technology
Tampere, Finland
e-mail: erja.sipila@tut.fi

***Abstract*— Nowadays there is an increasing interest to add functionality in various products and versatile electronics manufacturing methods are needed for different applications. In this study, brush-painting of silver nanoparticle UHF RFID tag antennas directly on wood veneer and polyimide film substrates was examined. Two sintering methods, heat and photonic sintering were tested for these antennas. According to our results, the tag antennas brushed on polyimide film showed read ranges of over 8 meters with both sintering methods. The tag antenna brushed on wood veneer did not respond after heat sintering, but showed a read range of about 2 meters after photonic sintering. The novel manufacturing process is presented and the achieved results are discussed in this paper.**

***Keywords*— antenna, brush-painting, polyimide, radio-frequency identification, silver nanoparticle ink, wood**

I. INTRODUCTION

The wood industry needs automated identification systems which will provide identification and tracking of wooden products throughout their whole lifetime: from production and warehousing to actual end products. Nowadays, identification during production and warehousing is mainly done manually by using various codes. Manual identification is prone to errors and misreads that could lead to delays or wastage. Also, external code labels can be easily damaged or lost. Radio-frequency identification (RFID) is an effective automatic identification technology for variety of objects [1]. The information can be restored throughout the lifecycle from the factory to the end user. RFID tags have already been applied to, e.g., wood logs for timber supply chain [2] and for plywood boards [3].

In addition, wood is a potential substrate material for various electronic applications. The inherent factors that make wood an interesting material to be used in electronics are many and varied, but the chief attribute is its availability in many species, qualities, sizes, and shapes to suit almost every demand. Wood has a high ratio of strength to weight and a remarkable record for durability and performance as a structural material. Dry wood has good insulating properties against heat and electricity. Wood is an aesthetically pleasing material, and it is easily shaped with tools and fastened with adhesives, nails, screws, bolts, and dowels. In addition, wood resists oxidation, acid, saltwater, and other corrosive agents, has high salvage value, has good shock resistance, can be treated with preservatives and fire retardants, and can be combined with almost any other material for both functional and aesthetic uses [4].

In this paper, the use of wood veneer (henceforth referred as wood) and polyimide film (henceforth referred as Kapton [5]) as a substrate for brush-painted ultra-high frequency (UHF) silver nanoparticle RFID tags is examined. Kapton is commonly used as a substrate for electronics and is thus also used here as an example. However, our future goal is especially to brush RFID tags on wooden substrates. By brush-painting the RFID tag antennas directly on wood and Kapton, we can manufacture very thin tags through eliminating the need for additional substrate material. This will also create material and cost savings, along with opportunities for novel applications. In some applications, e.g., in brand protection and antitheft solutions, brushing the tags directly on the substrate could provide additional value; the tags could be embedded as a part of the product and they cannot be removed from the product, at least not without breaking it. In addition, brushing the tag antennas directly on renewable and environmental-friendly substrates can in the future have a huge effect on the environment. These materials can replace currently used environmentally problematic materials, such as different kinds of polymer substrates, in electronics.

II. UHF RFID-TECHNOLOGY

The RFID system comprises tags, reader(s) and the background system. In RFID applications, the tags are attached or embedded into the objects that are to be identified or tracked. Each tag has an antenna and a microchip that stores the needed data, e.g., manufacturer or product type. The communication and coupling between the reader and the tags in RFID systems are based on radio frequency electromagnetic fields and waves, which has many advantages over other identification systems: Many items can be remotely identified simultaneously, no visual contact is needed, and reading through certain materials is possible.

RFID systems can be classified according to the operation frequency and according to the method of powering up the tag. Compared to active or semi-active tags, passive tags have shorter reading distances, they require higher-power readers and they are constrained in their capacity to store data. However, passive tags are simpler in structure, lighter in weight, less expensive, and generally more resistant to harsh environmental conditions. The passive technology shows promise in embedded applications since passive tags require very little maintenance and offer almost unlimited operational lifetime [6]. In this study, passive UHF systems are used, mostly because the read ranges of passive UHF RFID systems are longer compared to other used frequencies. Center frequencies used in UHF RFID systems vary globally, and they fall within the range from 860 MHz to 960 MHz [6]. See Figure 1 for a passive UHF RFID system.

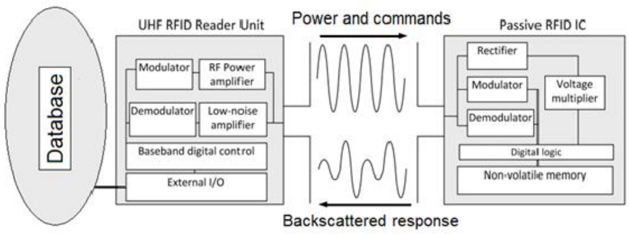


Fig. 1. Example of a Passive UHF RFID system, modified from [7].

In passive UHF RFID systems, the achieved response from the tag is affected by the circumstances and surrounding materials. The materials affect losses and change the feed impedance of the tag antenna. Materials also affect the radiation characteristics of the tag since current distribution depends on the electromagnetic properties of the surroundings. Especially liquid materials and metals near the tag will affect the tag functioning. Also the tag materials themselves have similar effects. Both the conductor material of the antenna (conductivity, thickness, surface roughness) as well as the substrate material (permittivity, loss tangent, thickness) have an effect on the tag functioning [8, 9].

Substrate materials may also cause indirect effects on the tag as the substrate affects the antenna morphology of the tag through its properties. This can have a significant meaning in the case of brush-painted RFID tags. The mechanical properties and the surface chemistry of the substrate both have a crucial role in the antenna brushed on it.

III. THE FABRICATION OF THE SAMPLE TAGS ON WOOD AND POLYIMIDE SUBSTRATES

Inkjet-printing has a proven track record of producing high performance RFID tag antennas on a variety of substrate materials [10, 11, 7, 12] and another interesting additive manufacturing method for RFID tag antennas is screen printing [13-14]. Prototype silver particle RFID tags have been printed on wood substrate by screen printing [13] and by inkjet printing [3], and sintered with heat. These manufactured UHF RFID tags have showed good performance on wood substrate; The screen-printed and heat-sintered tags with similar antenna geometry showed read ranges of 3-6 meters throughout the global UHF RFID band [13] and inkjet-printed and heat-sintered tags with similar tag antenna geometry achieved peak read ranges of 6.5 meters and read ranges of over 2 meters throughout the global UHF RFID band. However, their manufacturing has required many printed layers [3, 13], more than one printing-sintering round with different printing directions [13], and long sintering times in the oven (20-60 minutes). Several different sintering techniques such as laser, microwave, plasma and electrical sintering as well as sintering by chemical agents have been proposed to overcome this time problem, each naturally coming with different restrictions and shortcomings, and the best alternative to this time demanding thermal sintering process is also currently an interesting research area [15].

Next, we will introduce our manufacturing approach. Brush-painting is simple and fast method, which also enables mass production in the future. The manufacturing process involves only two process steps: painting and sintering, and it is possible to fabricate antennas with only one brushed layer, which means the fabrication method can offer a great competitiveness in future RFID tag manufacturing. The brushing-method not only reduces process-steps, but also minimizes the need of conductive material (ink), because the conductive material is dispensed directly to the brush, and from the brush directly to the antenna area in the substrate. In our study, the tag antennas (See Figure 2 for the antenna geometry) were brush-painted through a stencil (the material used as stencil was 50 μm thick polyimide film) on wood (1 mm thick wood veneer) and Kapton (20 μm thick polyimide film) by using only one layer of ink. The used ink was Harima NPS-JL silver nanoparticle ink [16], already used with success in RFID tag antenna prototype manufacturing by inkjet printing and heat sintering [3, 7].

Geometrical parameters in millimeters

L	W	a	b	c
100	20	14.3	8.125	2

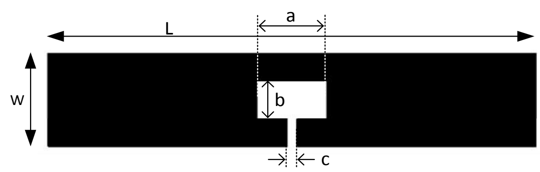


Fig. 2. Antenna geometry.

After brushing the ink through the stencil, the tag antennas were sintered with a photonic sintering system [17] that provides a high energy, pulsed light for reliable and efficient (extremely short processing time) sintering of conductive nanoparticles (also on heat sensitive materials). It has been successfully used to sinter silver nanoparticle ink [18]. The used sintering parameters (chosen after some initial testing) for wood and Kapton substrates can be seen in Table 1. We used only one single flash pulse in both cases. In addition, we sintered the tag antennas also with heat sintering, in 120 ˚C and 150 ˚C for 1 hour, in order to compare the results to those sintered with the photonic system. According to our measurements, the 150 ˚C sintering gave better conductivity for the antenna than the 120 ˚C sintering, so it was chosen. The manufacturing steps can be seen in Figure 3.

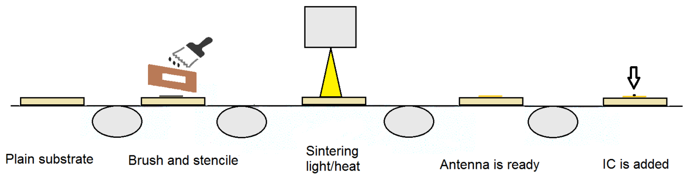


Fig. 3. Manufacturing steps.

A wood veneer surface is a challenging surface due to its porosity and high surface roughness. The ink is easily absorbed by the wood, preventing the nanoscale metallization particles, which are contained in the ink, to form a conductive layer. A unique characteristic of wood surfaces are their grain. A close-up examination of the grain reveals that the surface has valleys and hills that vary according to the grain (See Figure 4). In the direction of the grain such variations in the surface are low, whereas against the grain variations in the surface roughness are significant. In fact, in a previous study it was found out that tag antennas inkjet-printed on wood veneer only in one direction did not function even with several layers of conductive ink, and that tag antennas which had the antenna geometry printed along the grain showed the best performance [3]. This was also discovered in our preliminary tests: the conductivity of the antenna brushed against the grain showed significantly higher resistivity than the antenna brushed along the grain. Therefore, to maximize the performance and fabrication process throughput, tag antennas should be brushed along the grain. The spread of the ink on the wood veneer surface is also a major concern and thus the amount of used ink should be as small as possible.

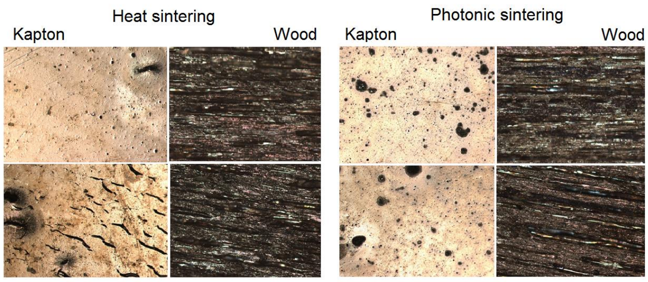


Fig. 4. Antenna surfaces after sintering. Photos taken from two different places in the same antenna.

The tag IC is NXP UCODE G2iL series IC [19]. The manufacturer had mounted the chip in a fixture patterned from copper on a plastic film. After sintering, we attached the pads of the fixture to the antenna material using conductive epoxy. In this study, we did not concentrate on IC bonding process; the goal of this paper is to investigate the ability of the novel additive manufacturing method on wood and Kapton substrate and the long term reliability of the joint is thus not relevant in this study. However, in future studies it is interesting to broaden the research work to that field.

TABLE I. SINTERING PARAMETERS IN PHOTONIC SINTERING SYSTEM.

Substrate	Wood	Kapton
Voltage (V)	3000	3000
Pulse time (us)	4000	3500
Pulse mode	single	single

IV. EVALUATION OF THE RFID TAG PERFORMANCE

All of the measurements made for this study were performed using Tagformance RFID measurement unit from Voyantic Ltd [20]. The core operations of the measurement device are performed with a vector signal analyzer. Tagformance was used to measure two key properties of passive UHF RFID tags: threshold power and theoretical read range. Both quantities can be measured as a function of transmit frequency or as a function of tag to reader antenna angle at a point frequency.

Threshold power describes the minimum transmit power, at the transmit port, to activate the tag. Theoretical read range describes the maximal distance between the tag and reader antenna in free space, i.e. environment without reflections or external disturbances; hence the term theoretical read range. Tagformance measurement system is able to calculate the theoretical read range of a tag using its measured threshold power along with the measured forward losses. The forward loss describes the link loss between the generator's output port to the input port of an equivalent isotropic antenna placed at the tag's location. The forward loss from the transmit port to the tag is calculated using a reference tag during the calibration procedure of Tagformance. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels. Theoretical read range can be therefore calculated using the following expression

$$d_{Tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{TS}L_{fwd}}} , \qquad (1)$$

where $EIRP$ is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, P_{TS} and L_{fwd} are the measured threshold power and forward losses, correspondingly.

V. RESULTS AND DISCUSSION

The measurement results for the theoretical maximum read range can be seen in Figure 5. As can be seen, the RFID tags on Kapton substrate showed peak read ranges of over 9 meters in the frequency range of 940-970 MHz (photonic sintering) and over 8 meters in the frequency range of 940-970 MHz (heat sintering, 150 ˚C for 1 hour). The heat-sintered RFID tag on wood substrate did not respond. However, the RFID tag on wood substrate manufactured by photonic sintering showed a read range of 5 meters throughout the global UHF RFID range, which is sufficient for many real life applications, e.g., in construction and packaging industry, where wood is a typical material.

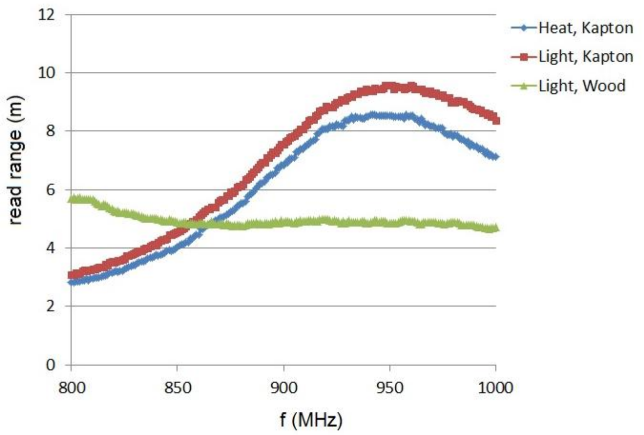


Fig. 5. Theoretical maximum read ranges.

These results show that manufacturing UHF RFID tag antennas by painting them with a brush through a stencil on different types of substrates and sintering them by photonic sintering has a great potential for future wireless applications. Thus, these brush-painted antennas offer an alternative to inkjet-printed and screen-printed antennas on wood substrates. It should be noted, that the brushing method is not suitable for structures containing very small details; if very small dimension are required, inkjet printing is recommended. However, with basic geometries, it is possible to achieve suitable read ranges with only one brushed layer.

In addition, there are many things to consider in our future research. In the case of the wood substrate, the ink spread is the highest in the direction of the grain. Therefore, tag antenna designs should be optimized so that there are no narrow gaps in the direction of the grain as the ink spread can cause short circuits in these areas. Also, in Figure 4 it can be seen that the surface of the antenna is not even on either substrate. Thus, the brushing method needs to be optimized for different substrates and a further analysis on the antenna surface structure is needed. Future work will also be the optimization of the amount of the ink used as well as sintering times and parameters in photonic sintering. We will also investigate the brush-painting of copper and nickel inks as an alternative to silver inks for potential cost reduction.

VI. CONCLUSIONS

Fabrication of antennas and electronics directly on different substrates, including wood and other renewable materials is imperative for the development of future wireless platforms. We presented prototypes of passive UHF RFID tags with antennas brush-painted on wood and polyimide substrates without any surface treatments, using only one layer of silver nanoparticle ink, and sintered with heat and photonic methods. According to their measured performance, these paint-brushed antennas offer a high potential for future wireless applications, especially when photonic sintering is used. However, a lot of work is still needed for the optimization of the novel manufacturing process.

REFERENCES

[1] E. Welbourne, L. Battle, G. Cole, K. Gould, K. Rector, S. Raymer, M. Balazinska, G. Borriello, "Building the internet of things using RFID: The RFID ecosystem experience," IEEE Internet Comput., vol. 13, no. 3, pp. 48-55, May-June 2009.

[2] S. Korten, and C. Kaul, "Application of RFID (Radio Frequency Identification) in the timber supply chain," Croatian Journal of Forest Engineering, vol. 29, no. 1, pp. 85-94. June 2008.

[3] J. Virtanen, J. Virkki, L. Sydänheimo, M. Tentzeris, and L. Ukkonen, "Automated identification of plywood using embedded inkjet-printed passive UHF RFID tags," IEEE Trans. Autom. Sci. Eng., vol. 10, no. 3, pp. 796-806, July 2013.

[4] Wood Handbook — Wood as an Engineering Material. Madison, Wisconsin: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, April 2010.

[5] DuPont™ Kapton®, http://www2.dupont.com/Kapton/en_US/ (3.1.2014)

[6] D. Dobkin, RF in RFID - Passive UHF RFID in Practice. Elsevier, 2008.

[7] J. Virtanen, J. Virkki, L. Ukkonen, and L. Sydänheimo, "Inkjet-printed UHF RFID tags on renewable materials," Advances in Internet of Things, vol. 2, no. 4, pp. 79-85, September 2012.

[8] S. Merilampi, T. Björninen, A. Vuorimäki, L. Ukkonen, P. Ruuskanen, and L. Sydänheimo, "The effect of conductive ink layer thickness on the functioning of printed UHF RFID antennas," IEEE special issue, RFID - a Unique Radio Innovation for the 21st Century, Vol. 98, no. 9, pp. 1610-1619. September 2010.

[9] R. Schmitt, Electromagnetics explained - A Handbook for Wireless/RF, EMC, and High-Speed Electronics. Elsevier, 2002.

[10] A. Rida, Y. Li, R. Vyas, and M.M. Tentzeris, "Conductive inkjet-printed antennas on flexible low-cost paper-based substrates for RFID and WSN applications," IEEE Antennas Propagat. Mag., vol. 51, no. 3, pp. 13-23, June 2009.

[11] G. Orecchini, F. Alimenti, V. Palazzari, A. Rida, M.M. Tentzeris, and L. Roselli, "Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology," IET Microwaves Antennas Propag., Vol. 5, no. 8, pp. 993-1001, June 2011.

[12] K. Sangkil, B. Cook, L. Taoran, J. Cooper, L. Hoseon, V. Lakafosis, R. Vyas, R. Moro, M. Bozzi, A. Georgiadis, A. Collado, and M.M. Tentzeris, "Inkjet-printed antennas, sensors and circuits on paper substrate," IET Microwaves Antennas Propag., Vol. 7, no. 10, pp. 858-868, July 2013.

[13] J. Virkki, S. Merilampi, L. Ukkonen, and L. Sydänheimo, "Performance of UHF RFID tags printed directly on plywood structures," International Journal of RF Technologies: Research & Applications, Vol. 3, no. 4, pp. 283-302, July 2012.

[14] T. Kellomäki, J. Virkki, S. Merilampi, and L. Ukkonen, "Towards washable wearable antennas: A comparison of coating materials for screen-printed textile-based UHF RFID tags," Int. J. Antennas Propag., Vol. 2012, Article ID 476570, 2012.

[15] B. Polzinger, F. Schoen, V. Matic, J. Keck, H. Willeck, W. Eberhardt, and H. Kueck, "UV-sintering of Inkjet-printed Conductive Silver Tracks," Proceedings of the 11th IEEE Conference on Nanotechnology, Portland, Oregon, USA, August 15-18, 2011.

[16] Harima, NPS-JL silver nanoparticle ink, NanoPaste series, metal paste for thin film formation, Datasheet, http://www.harima.co.jp/en/products/pdf/16-17e.pdf (13.12.2013)

[17] XENON SINTERON 2010 Sintering system, http://www.xenoncorp.com/sintering_products.html (12.2.2014)

[18] T. Falat, J. Felba, B. Platek, T. Piasecki, A. Moscicki, and A. Smolarek, "Low-temperature, Photonic Approach to Sintering the Ink-jet Printed Conductive Microstructures Containing Nano Sized Silver Particles," Proceedings of the 18th European Microelectronics and Packaging Conference (EMPC), Brighton, UK, September 12-15, 2011.

[19] NXP UCODE G2iL IC Datasheet, http://www.nxp.com/documents/data_sheet/SL3S1203_1213.pdf (13.2.2014)

[20] Voyantic, Ltd., Espoo, Finland, http://www.voyantic.com/ (10.12.2013)

Tampereen teknillinen yliopisto
PL 527
33101 Tampere

Tampere University of Technology
P.O.B. 527
FI-33101 Tampere, Finland

ISBN 978-952-15-3822-3
ISSN 1459-2045