TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

HAN HE

OPTIMIZATION OF FABRICATION PARAMETERS FOR INKJET PRINTED RFID TAGS ON PAPER-BASED SUBSTRATES

Master of Science thesis

Examiner: Postdoctoral Researcher Johanna Virkki and Professor Leena Ukkonen
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ABSTRACT

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Inkjet printing is a non-contacting additive depositing method for fabricating electric devices on versatile substrates, which provides a great potential for different Internet of Things (IOT) applications. It enables fast, cost-effective, and environmentally friendly production. Paper-based substrates, like coated paper, uncoated paper, and cardboard are used for printed patterns, and silver nanoparticle ink is applied in this study. Printed layers need to be sintered to form conductive traces, and in this experiment, thermal sintering is selected, since it is easy to operate and has stable performance.

The aim of this thesis is to study the possibility of inkjet printing on paper-based substrates using silver nanoparticle ink and to optimize the printing parameters for fabricating passive ultra-high frequency (UHF) radio frequency identification (RFID) tags on these substrates. A simple line pattern with dimension of 5mm × 30 mm was first printed on these substrates to evaluate the conductivity, and surface magnified images from the optical microscope were taken to analyze the performance.

The silver nanoparticle ink was successfully sintered with thermal sintering on three paper substrates and four cardboards. For every substrate, specific printing parameters and layers are needed to achieve best conductivity performance. Then, inkjet-printed UHF RFID tags were fabricated on these substrates. According to our measurements, the tags on paper substrates showed peak read ranges of 4 – 6.5 m, and the tags on cardboard substrates exhibited peak read ranges of 1 – 6 m. Based on these results, the performance of these inkjet-printed UHF RFID tags is sufficient for many IOT devices and potential applications.

PREFACE

This Master of Science thesis work was carried out in the Wireless Identification and Sensing Systems Research Group, in the Department of Electronics and Communications Engineering at Tampere University of Technology.

I would like to thank my supervisors, Dr. Johanna Virkki and Prof. Leena Ukkonen. I appreciate the opportunity to work on such an interesting project and I am deeply grateful for all the trust, guidance and encouragement they gave me throughout the work.

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LIST OF SYMBOLS AND ABBREVIATIONS

CIJ	Continuous Ink Jet
DOD	Drop-on-Demand
HF	High Frequency
IC	Integrated Circuits
IPL	Intense Pulsed Light
LF	Low Frequency
OLED	Organic Light Emitting Diode
PE	Printed Electronics
PEN	Polyethylene Naphthalate
PET	Polyethylene Terephthalate
RFID	Radio Frequency Identification
UHF	Ultra-high Frequency

ω	Angular frequency
μ	Permeability
σ	Conductivity
λ	Wavelength
f	Frequency

1. INTRODUCTION

Printed electronics (PE) is a novel technology which manufactures electrical devices on various unconventional substrates such as cardboard, wood, paper and plastic [1]. As an additive depositing process, PE defines designed patterns on substrates by using a set of common printing technologies, such as screen printing, inkjet printing, flexography and gravure printing. Printed electronics has various advantages like cost-effectiveness, time saving and environmental-friendliness, which make it widely used in flexible displays, smart labels, decorative and animated posters, and active clothing.

A piezo drive inkjet printing is a prominent method among a variety of printing methods since its great compatibility with functional inks. Inkjet printing is a non-contact material deposition method which uses various inks jetted from the printhead to form droplets on substrates. It provides various benefits, such as low-cost, fast fabrication and high precision. Thus, it has a wide range of application like organic light-emitting diodes (OLEDs), flat panel displays and radio frequency identification (RFID) tags [2].

For inkjet printing technology, both metallic nanoparticles and electrically conductive polymers are used as printing inks. Normally, metallic nanoparticles, including silver (Ag), gold (Au), Nickel (Ni) and copper (Cu), can achieve better conductivity than conductive polymers. Metallic nanoparticle ink always consists of liquid element (metallic nanoparticles) and the dispersed or dissolved element. In this experiment, silver nanoparticle ink is selected to form conductive patterns by inkjet printing since its high conductivity and silver oxide is also conductive.

After printing, sintering is a very important process to remove the useless solvent and organ materials from the ink. Thermal sintering process, which heats the printed patterns in the oven, is the most popular sintering method. It is very easy to operate and has stable performance, but there are also some disadvantages like long sintering time. For the ink used in this study, one-hour sintering with 150°C is recommended to achieve good conductivity. There are also other sintering methods available, such as intense pulsed light sintering (IPL), laser sintering, plasma sintering and microwave sintering [3].

The goal of this thesis work is to study the possibility of inkjet printing on various paper-based substrates provided by company Valmet and optimize printing parameters for fabricating passive UHF RFID tags on these substrates. The used ink is NPS-JL NanoPaste® silver ink from Harima chemicals Inc.

The outline of this thesis is described as follows. Chapter 2 introduces basic knowledge of RFID technology including the structure of the typical RFID system and the classification of RFID systems. Chapter 3 focuses on inkjet printing technology which is used to fabricate RFID tags in this thesis. Also, fundamentals of inks, substrates and sintering methods are included. The materials, tools and methods of experiment are described in Chapter 4, conductivity measurement of printed lines on every substrate is also shown in this chapter. In Chapter 5, passive UHF RFID tags are fabricated and measured, the theoretical read ranges are also plotted for analyzing. Finally, the thesis is concluded in Chapter 6.

2. RFID

2.1 Overview of RFID system

Radio frequency identification (RFID) is a wireless identification and tracking technology to automatically identify physical objects and write/read data by using radio frequency (RF) waves. As a non-contact automated technology, RFID has various advantages, for instance, it can read multiple devices simultaneously, it can operate under severe environment, and line-of-sight is not necessary when scanning RFID tags. In addition, labor saving can be achieved with RFID technology. Due to these advantages, RFID obtain widespread availability in supply chain management, access control systems, human and animal tracking devices, point-of-sale application and logistics application [4].

For a typical RFID system which is shown in Figure 1, there are three core components: a tag (aka a transponder), a reader (aka an interrogator), and a controller (aka a host). The tag contains an antenna and a semiconductor integrated chip (IC) capable of storing the identification code. The reader, including an antenna, an RF interface and a control section, is able to read and write tag information. The host consists of a middleware and a PC (enterprise application). The middleware is required to connect with the reader directly and control the reader and PC is used for processing the collected data [5].

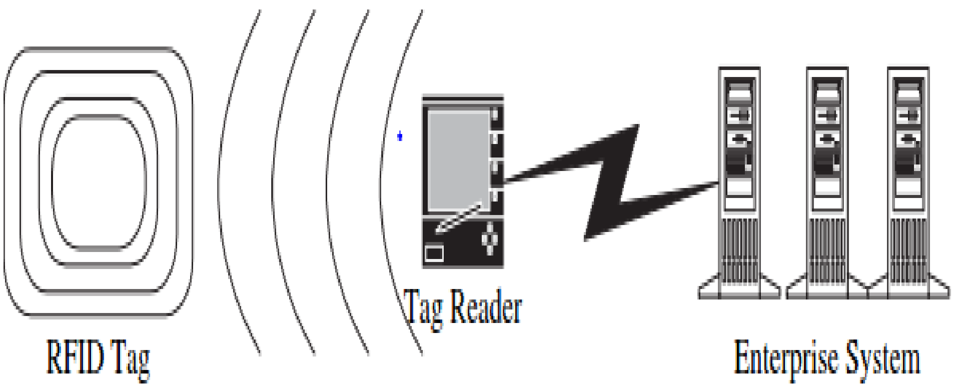

Figure 1 A typical RFID system [6].

When a RFID tag enters the interrogation zone of a reader, the reader can connect with the tag to collect the information of the attached item, such as color, size, manufacture data, serial numbers, configuration instructions and current price, which will be processed by the host computer [7]. An intelligible description of RFID system is the master-slave principle, as shown in Figure 2. Without the electromagnetic wave from the reader, the (passive) tag is failed, therefore, we consider the reader as a master and tag as a slave. In addition, there is also master-slave relationship between the reader and the host application. As a master, the host always sends command and controls the reader after process the identification information.

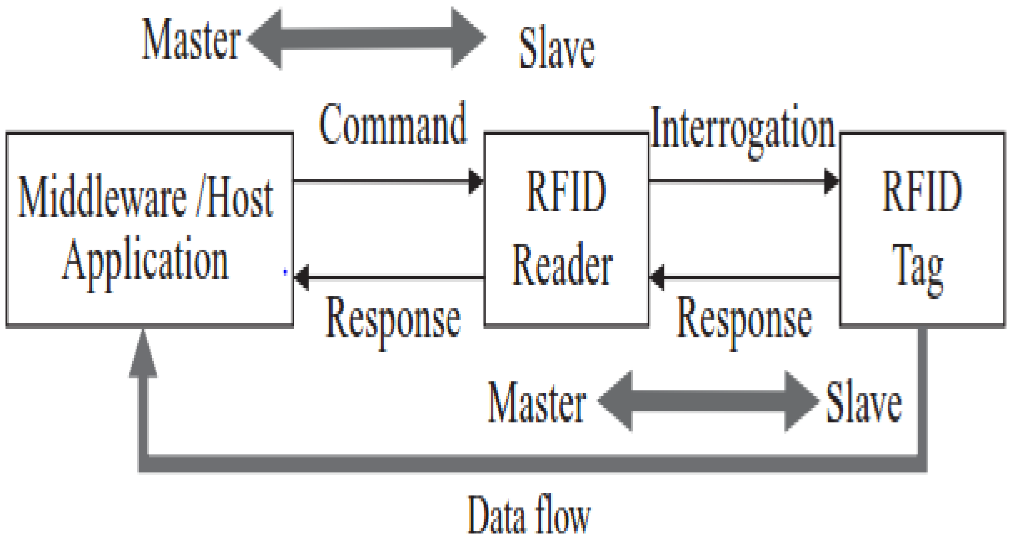

Figure 2 Master-slave principle [5].

2.2 Classification of RFID system

Based on the power source, frequency of operation and read/write capability, RFID system can be classified distinctly.

2.2.1 Active, semi-passive and passive tags

Due to different power supply, RFID tags are segmented into active, semi-passive and passive tags. Passive tags do not have their own power source which can operate the IC. Therefore, the electromagnetic wave from the reader is necessary for tag to power up the IC and reply to the reader. The radiated signal from the reader always induces a voltage, which produces the backscattered wave to the reader. Moreover, to modulate the backscattered wave with the tag information, a switchable transistor, which acts as a load to vary the input impedance, is utilized. [8] The backscatter modulation principle is shown in Figure 3. Due to the lack of on-board battery, the passive RFID tags have shorter effective read range and less storage space compare with active tags since the limitation of the power. On the other hand, passive tags have extremely small size, lowest cost as well as simple manufacturing process, which make them have a wide range of application.

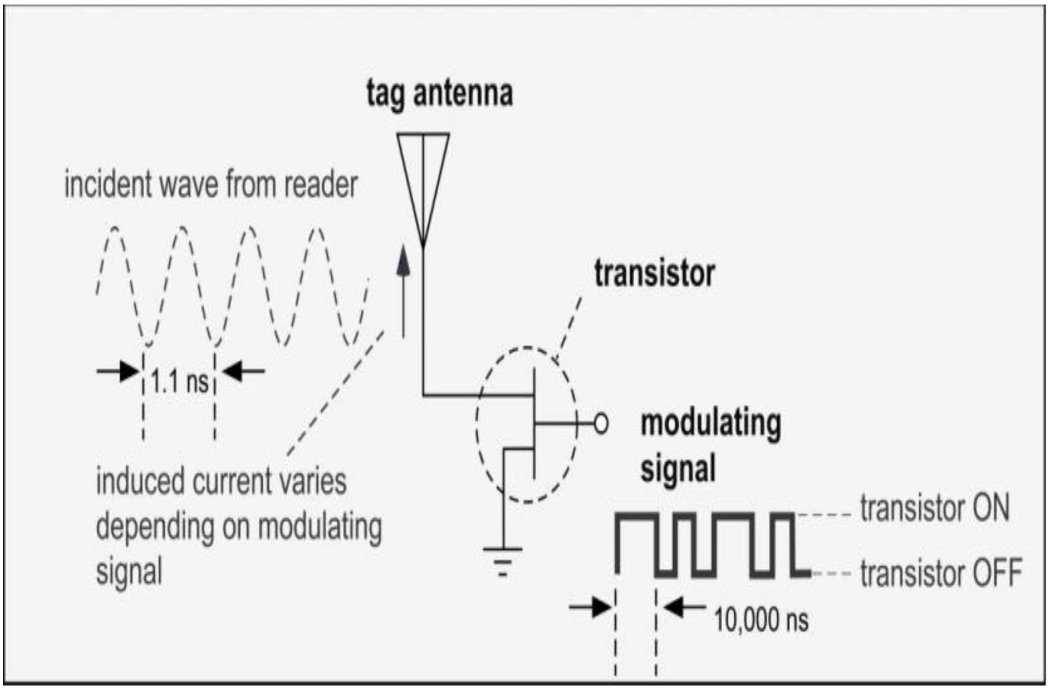

Figure 3 Modulated backscatter using a transistor as a switch [9].

Semi-passive Tags, also known as battery-assisted tags (BATs), contain batteries on-board, only to power the IC and maintain it. They do not include any transmitter, hence, backscatter coupling is required to communicate with the reader. Compared with passive tags, semi-passive tags have higher storage space, longer read ranger but also higher cost and larger size. Continuous power source enable them to work as environment sensors, such as pressure and temperature, but limited stability will restrict the usage of tags under severe environment [5].

On-board power supply is necessary for active tags, which provide high power for transmitting information to the reader. In addition, with their own transceiver, active tags actually act as the reader [5]. Because of high transmitting power, they can reach the longest read ranges, up to several kilometers sometimes. Also, they have higher memory capacity than other types of tags. However, shortcomings such as largest size, highest price and finite lifetime of battery limit the usage of active tags.

2.2.2 Operation frequency band

The frequency band, another key criterion for classifying the RFID system, divides RFID tags into follow types: low-frequency (LF) Tags, which operate at 125-134 KHz.

High-Frequency (HF) Tags,which operate at 13.56MHz. Ultra-high-frequency (UHF) Tags, which operate at 860-960 MHz. And microwave tags, which operate at 2.5GHz and above. The total radio frequency spectrum for RFID systems is shown in Figure 4.

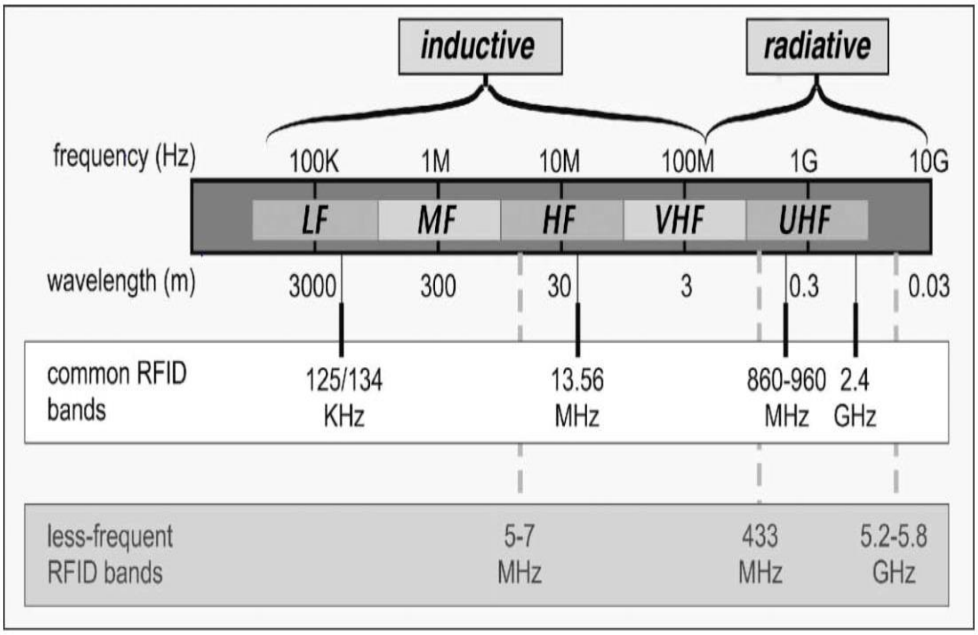

Figure 4 RFID frequency bands [8].

Compared with the antenna size, LF tags and HF tags have larger wavelength while UHF tags and microwave tags have smaller wavelength. Usually, LF passive tags and applied to short-range devices, such as patient monitoring, human and animal tracking and livestock identification. Due to limited anti-collision ability as well as low memory capacity, these tags are not applied to complex environmental conditions [5].

Similar with LF tags, HF tags are also in passive type with near-filed inductive coupling. Although they have a bit longer read range as well as higher speed of data processing than LF tags, the read range is still the limitation to obtain a wide range of application. Due to less cost and complex, these tags are mostly used in baggage tracking, library database management and small product labeling [5, 9]. HF tags are the most popular tags around the world currently.

UHF tags, as passive and semi-passive tags, send data to the reader by backscatter coupling. They have high effective read range and good anti-collision quality, thus, they can communicate with multiple readers simultaneously.

Microwave tags can work as passive, semi-passive and also active tags. They have smallest size, highest effective read range and widest available frequency range. Due to these advantages, these tags have various applications, for instance, highway toll collection, fleet identification and real-time location system [5].

2.3 Passive UHF RFID tag antennas

In the coming years, passive UHF RFID system share a high potential in wireless technology. Normally, the spectrum of UHF is 860MHz to 960MHz, but the center frequencies are different according to the countries, which are shown in Table 1. There are numbers of advantages of this technology as a combination of passive and UHF tags, such as small size, light weight, long lifetime and high anti-collision quality.

Same with other passive tags, UHF RFID tags communicate with readers by the backscatter coupling. Since these tags do not include any power source such as on-board batteries, the radio waves from the readers provide all the power for activing the IC.

In an UHF RFID system, the tag performance depends on the properties of the substrate to some extent. The surrounding materials of tags can influence losses and impedance matching of the tag antenna [11]. In addition, substrate can also affect the current distribution which will change the radio characteristics [12]. In conclusion, the properties of the materials used as both conductive antennas and substrates should be under consideration to obtain satisfying tag performance.

Table 1 UHF Frequency bands [8]

Region area	Frequency Band (MHz)
Europe	865.6-867.6
United states Canada	902-928
Japan	952-956.4
China	920.5-924.5

3. INKJET PRINTING TECHNOLOGY

Printed electronics, including flexography printing, gravure printing, screen printing and inkjet printing, are used for generating electronic patterns on different substrates. As a combination of electronics fabrication and printing technique, this technology can provide very low-cost, flexible, wearable, lightweight, and eco-friendly products, for instance, organic photovoltaics, smart cards, displays, OLED and active clothing [6].

This thesis will focus on inkjet printing technology on different environmental-friendly substrates, such as paper and cardboard. The background, classification and working mechanism of inkjet printing will be introduced in this chapter.

3.1 Inkjet printing process

As a non-contact material deposition technology, inkjet printing can create a specific pattern by dropping the ink directly from an aperture to the printed substrate, including paper, transparencies, wood veneer, cardboard and polyimide film. With a wide range of application, inkjet printing is playing a more and more important role in modern technique society, especially in home and office application. Furthermore, compared to other printing technologies, inkjet printing has various benefits, including low fabrication cost, low waste, high precision, high resolution and printing process has high automation [13, 14].

Inkjet printing is primarily divided into two methods, continuous inkjet printing (CIJ) which the ink is shot out constantly, and drop-on-demand (DoD) method, where drops are only ejected when required [11,13]. Figure 5 shows the classification of inkjet printing technologies.

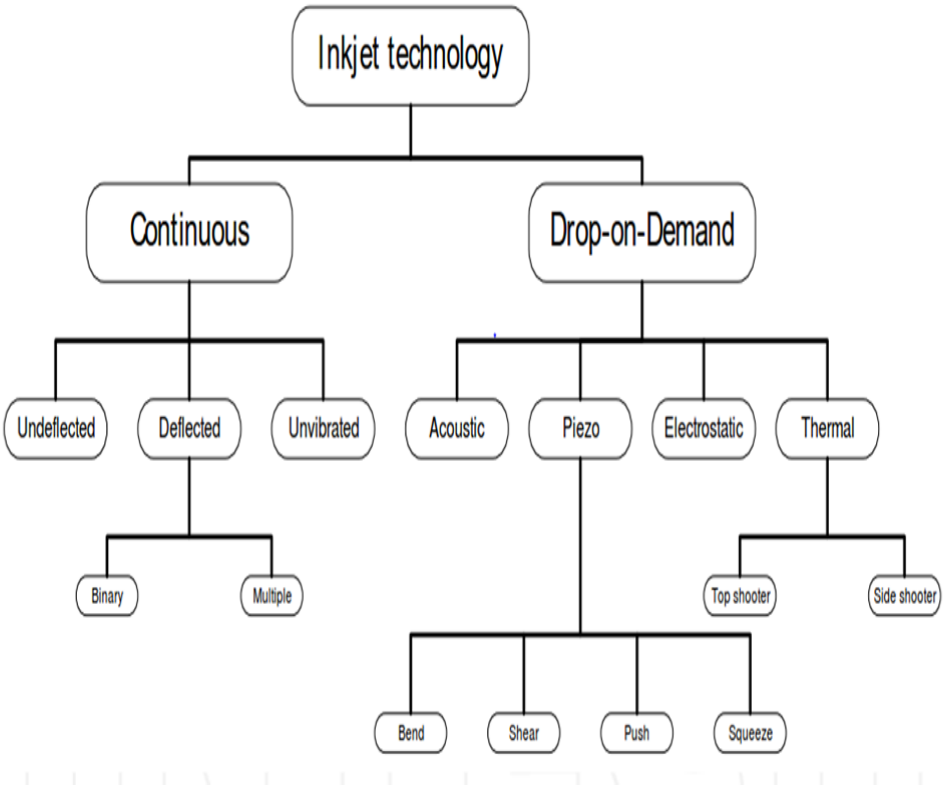

Figure 5 Classification of inkjet printing technologies [13].

In CIJ printing method, that sprays a falling stream of ink through a small orifice, the fluid separates into small discrete drops due to Plateau Rayleigh instability [14]. With the electric charge, droplets can be deposited into required positions by adding the static electric field. Since droplets through electrode charge with different voltages have totally different flight path, controlling the position of the deposition on substrate can be achieved. In addition, useless drops will be deposited to the recycling gutter for reusing again [14].

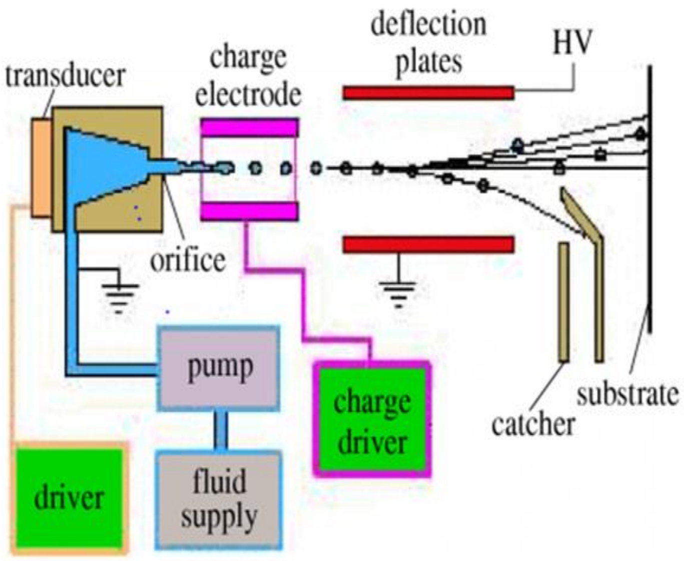

Figure 6 Process of continuous inkjet printing [15].

Drop-on-demand method is the most important and mature classification of inkjet printing technology. Different from the CIJ, the printer ejects the drops from the nozzle on demand. Since there are four different drop formation methods, the DOD technology can be categorized into four primary subclasses, which are thermal, piezoelectric, electrostatic, and acoustic ink-jet [11, 16]. The most popular methods are thermal and piezoelectric.

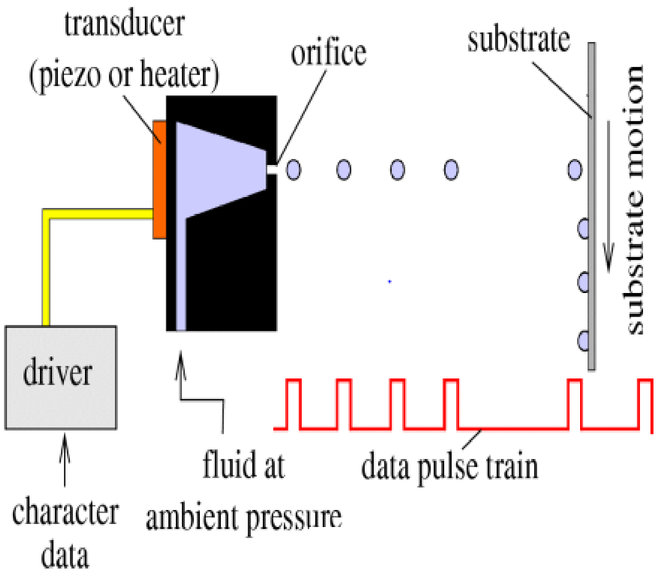

Figure 7 Process of drop-on-demand inkjet printing [15].

Thermal DoD inkjet, also called Bubble jet or the inkjet, is popular in desktop printing application. During this method, by heating a thin film resistive element rapidly, a small fraction of ink will become gaseous, which generate a pulse that eject drops through a small orifice [13, 16]. The drops formation process is shown in Figure 8.

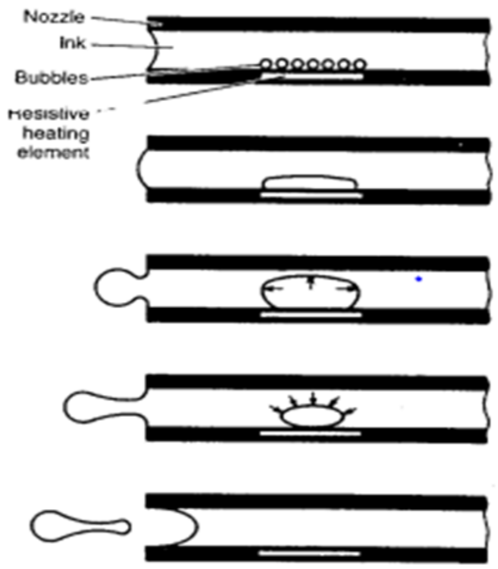

Figure 8 Drop formation process [16].

Currently, piezoelectric inkjet printing has better performance than thermal method, especially for printed electronics using conductive nanoparticle inks, because in thermal mode, high temperature of the heating resistor will result in the sintering of inks [17]. Piezoelectric inkjet has a wide range of application in industrial inkjet printing. To form droplets, the pressure pulse is applied to the piezoelectric transducer to eject drops from nozzles. By adjusting the waveform of the jetting voltage, the generation frequency, volume and speed of droplets can be controlled so the drops can be deposited in required positions accurately. The print head, including a number of nozzles, is actuated by the electric motor to move in a specific direction while the platen can move orthogonally. Thus, two-dimensional patterns can be printed easily.

The size of droplets on the substrates depend on various factors, such as cartridge temperature, jetting voltage, jetting frequency, the substrate temperature and the surface property of the substrate. After inkjet printing, the sintering process is necessary to obtain a conductive trace.

3.2 Inks for inkjet printing

In terms of printed electronics, there are numbers of inks utilized, such as dielectric inks, semi-conductive inks, conductive inks, and resistive inks.

For inkjet printing technology, conductive inks are the most common ones, and some magnetic and semiconductor inks have also been developed. However, conductive inks usually have a relatively high resistivity. Alternative metallic nanoparticle inks can provide a resistivity as low as several times the resistivity in bulk metal.

There are two fundamental parts of functional inks, which are the liquid element and the dispersed or dissolved element. The liquid element, which can be a kind of organic solvent, decides the basic properties. The dispersed element such as metal particle can provide specific function [17]. The size of printer nozzles is extremely small, thus, avoid blocking of nozzles, the diameter of particles should be small enough, which is no more than 1-5 percent of the nozzle size [14]. In addition, since the melting temperature is closely related to the particle size, nanoparticles can easily melt at lower temperature compared with large particles [18]. As a result, nanoparticle conductive ink should be the best choice of inkjet printing technology.

The diameter of particles in nanoparticle conductive inks is 1 to 100 nm. Due to the small size of particles, this ink has several advantages, such as ease of dispersal in many solvents, high purity and high metal loading [14]. Usually, high conductivity metal such as gold, silver and copper are used for nanoparticle inks. Copper ink is easily oxidezed in ambient environment and copper oxide is an insulator. Silver has high conductivity and the silver oxide is also conductive. Thus, silver it is widely used in nanoparticle inks [19]. However, the relatively high cost of silver ink and long sintering time limit the wide usage of the ink in mass industrial fabrication. In addition, since good conductivity and low cost, copper also has a high potential in printing industry. But copper nanoparticle is rapidly oxidized, so an anti-oxidation shell such as silver, gold and platinum is usually required.

3.3 Substrates

The substrates for inkjet printing are required to be flexible, heat resistance, low-cost, smooth-surface, thin, and low thermal expansion, because the properties of substrates will decide the performance of printing and available sintering method [20].

The glass substrate has a wide range of usage in optical application, such as displays and lighting. With the development of the material industry, the thickness of glass substrate can reach 30μm. On the other hand, due to the high cost, low flexibility and high weight, the further development is required for widely commercial usage.

Polyethylene terephthalate (PET) film is the majority plastic film which is an ideal choice as flexible substrates. Although with high transparence and low cost, the low thermostability limits the usage of this substrate [21]. To overcome this problem, polyethylene naphthalate (PEN) and polyimide (PI), which have higher heat resistance are introduced. However, PEN and PI have several drawbacks such as higher cost and lower transparence.

Paper substrate, which is low-cost and disposable due to its biodegradability, has various of application, such as one-off RFID tags without the Si chip. Nanocellulose paper, which has high transparence, high heat resistance, and low thermal expansion, attracts lots of attention.

Wood veneer substrate and cardboard substrate are also interesting selection. They are common used in product packaging since the advantages such as eco-friendly and low-cost [22]. However, due to the porosity of the surface, the drops are easily absorbed by the substrate, which destroy the shape of droplets and the conductivity of the printed patterns.

3.4 Sintering

The sintering is a significant process in inkjet printing technology, which mainly removes the useless solvent and organ materials from the ink. After sintering, the printed patterns on substrates become conductive since the direct physical contact between metal nanoparticles which form a solid mass [23]. The sintering process is an important consideration for inkjet printing technology. The sintering sometimes consumes most of the time during the inkjet printing process, which will influence the speed of manufacture directly. In addition, the sintering temperature can limit the selection of the available substrates.

To achieve a well-sintered printing trace, numbers of sintering method are applied, such as thermal sintering, laser sintering, intense pulsed light sintering (IPL), plasma sintering, and microwave sintering. Among these methods, thermal sintering is the most conventional one while laser and IPL sintering have high potential in printing application due to their high efficiency.

3.4.1 Thermal sintering

Thermal sintering is the most commonly used sintering method for nanoparticle inks. By using a normal oven, the printed patterns are easily heated to merge into a continuous conductive trace. To avoid the oxidation of the metal nanoparticles, inert gas such as hydrogen and nitrogen can be used during the heating process. Typically, high heating temperature is needed, which is up to 300 °C normally, to burn off the organic additives and form neck between particles [24]. Sintering time depends on the materials of the ink and varies from few minutes to one hour. Harima NPS-JL silver NanoPaste ink used in this work, recommends sintering at 120°C to 150°C for one hour. Normally, with longer sintering time and higher temperature, the sintered patterns should have better conductivity performance [25].

3.4.2 Laser sintering

Laser sintering is based on the photonic energy which can be absorbed by the inkjet-printed patterns. By scanning with a small spot over the whole printed area, the power density of the absorbed coherent light is extremely high, which results in high conductive performance of the printed layers [26]. Laser sintering is used for high-accuracy printing that different sintering parameters can be achieved in different printing areas, which results in different conductivity. However, this method is extremely time-consuming especially for large patterns.

3.4.3 IPL sintering

Intense pulsed light sintering (IPL) is similar with laser sintering but with different operating method. The printed layers are sintered with pulsed light over a broad spectrum, which is emitted by a scalable xenon flash lamp [26]. After being absorbed by dark nanoparticles, the high concentrated light is easily transform into the heat energy, which lead to the melting of the nanoparticles and formation of the conductive patterns. On the other hand, the substrates, such as paper, plastic film and cardboard, which are always light-colored, will not be heated due to the reflection. Compared with laser sintering, this method has a higher operation rate.

4. EXPERIMENT

4.1 Materials and tools

4.1.1 Ink and substrates

In this the experiment, the used ink is NPS-JL NanoPaste® silver ink from Harima chemicals Inc. Table 2 shows the main specifications of the silver ink, which was used to print simple line patterns to find the optimum parameters and then to fabricate passive UHF RFID tags.

Table 2 Specifications of the utilized nanoparticle ink [27].

Ink	Ag NPS-JL NanoPaste®
Solid content (wt%)	52-57
Particle size (nm)	5-12
Average particle size (nm)	7
Resistivity (μΩ·cm)	4-6
Viscosity (mPa·s)	11.5 (measured at 20°C and 60 rpm)
Recommended thermal curing	120-150 °C for 60 minutes

As shown in Table 3, passive UHF RFID tags are printed on nine kinds of substrates which were provided by company Valmet. Different parameters are applied in every substrate to achieve best performance.

Table 3 Substrates used for inkjet printing

Substrate	Thickness	Speciation
4104/P1	100 µm	coated , no calendering
4104/648		uncoated paper
4095/413	80 µm	coated , calendered
4095/214		double coated : film + blade, matt finish paper
4095/204		film coated, matt finish paper
4083/219	500 µm	double coated
4083/207		pre-coated
4083/P8		base board
4083/618		pre-calendered

A coating is a covering that is applied to the surface of the paper substrate. With a glossy or matte finish, a coated substrate generally has very smooth and shiny (high gloss) surface. Thus, the coated substrate always has a great performance on the appearance and usefulness of the printed item. In addition, coating can restrict the amount of ink that is absorbed by the paper. On the other hand, uncoated substrate has generally more absorbent of ink than a coated paper, like its namesake, uncoated paper does not have a coating. It is generally not as smooth as coated paper and tends to be more porous.

Coatings are primarily divided into several methods, such as direct coating, blade coating, film coating, and transfer coating. The substrates used in this experiment are normally blade coated and film coated. Blade coating, also known as doctor blading, is a widely used coating method to produce thin films on large area surfaces. The layer is formed by a doctor blade that is either stationary when used with a moving casting surface, or by a frame that moves along a stationary casting surface. With regard to film coating, it is a thin polymer-based coat on the solid dosage form, such as the paper and cardboard.

Furthermore, the calendaring is also important for fabricating the substrates. It is a finish process, which uses series of hard pressure rollers to form or smooth a sheet of material such as paper or plastic film.

4.1.2 Inkjet printer and cartridge

As shown in Figure 9, Fujifilm Dimatix DMP-2831 material inkjet printer, which has a platen area of 210mm × 310mm, is used for depositing ink droplets. This printer can create and define patterns and handle substrates up to 25 mm thick with an adjustable Z height. The temperature of the vacuum platen, which secures the substrate in place, can be adjusted up to 60°C. A plenty of printed patterns can be designed by using a pattern editor program. The resolution of patterns range from 100 dot-per-inch (dpi) to 5080 dpi to fit different droplet spacing from 254 µm to 5 µm. Additionally, a 10pL volume cartridge which has a snap-in replaceable print head with 16 nozzles is applied to ejecting the drops. To optimize the characteristics of drops ejected from the nozzle, a waveform editor and a drop-watch camera system are used to manipulate the electronic pulses to the piezo jetting device.

Figure 9 Fujifilm Dimatix DMP-2831 material inkjet printer

4.2 Pattern resolution

Pattern resolution is one of the most important parameters which should be determined firstly before the printing. Every substrate should have its own specific resolution which leads to uniform printed pattern and good conductivity. Printing with too high resolution can cause bulging and too low resolution results in isolated drops [27]. Normally, an appropriate droplet spacing, which can result in satisfying connection without unnecessary spreading, is normally equal to the radius of the drop (half of the drop size). In this study, Olympus Optical Microscope is used to measure the drop size when a drop size test pattern is printed. The droplet size depends on the material of the substrate, properties of the ink and print head settings. The selected resolution of every substrate is listed in Table 4.

Table 4 Printing resolution of every substrate

Substrate	Average drop size (µm)	Angle (degree)	Resolution (dpi)
4104/P1	110	11.4	508
4104/648	110	11.4	508
4095/413	90	9.1	635
4095/214	95	10.2	564
4095/204	95	10.2	564
4083/219	90	9.1	635
4083/207	105	11.4	508
4083/P8	105	11.4	508
4083/618	105	11.4	508

The droplet size of silver nanoparticle ink on paper 4095/413 is shown in Figure 10. Most of drops are ideal circles and have similar size. As a comparison, the shape of drops on uncoated paper 4104/P1 is irregular and the size is various. In addition, on this paper substrate, absorption can be observed from optical microscope, as shown in Figure 11.

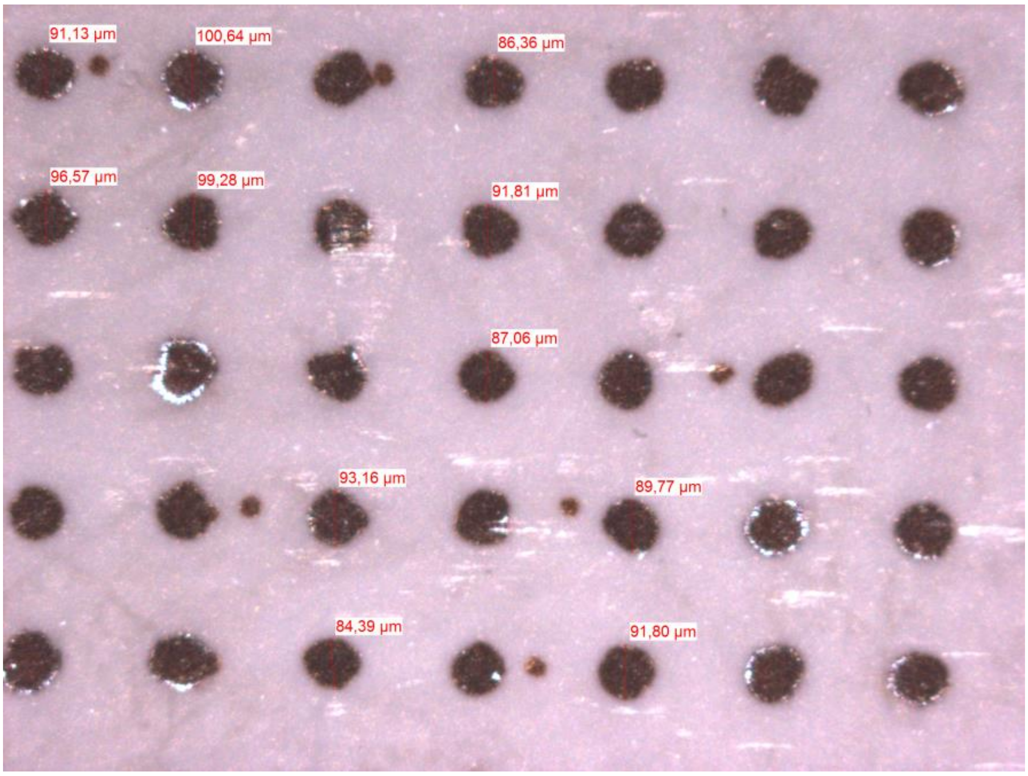

Figure 10 Droplets measurement on paper substrate 4095/413

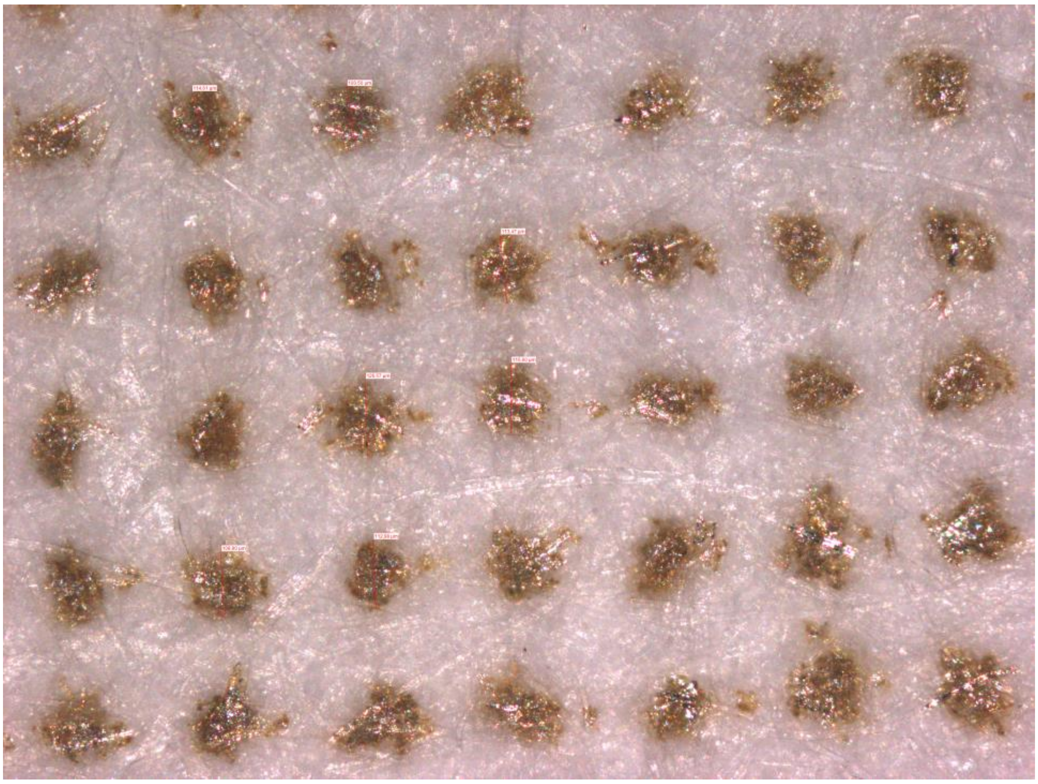

Figure 11 Droplets measurement on paper substrate 4104/P1

Table 5 indicates the printing settings for silver nanoparticle ink which were kept identical for all substrates. After all parameters are determined, simple line patterns with dimensions of 5 mm × 30 mm are printed on all substrates.

Table 5 Silver nanoparticle ink printing parameters

Cartridge temperature (°C)	40
Platen temperature (°C)	50
Jetting voltage (V)	28
Jetting frequency (kHz)	23
Sintering time (minutes)	60
Sintering temperature (°C)	150

During the printing process, multilayer printing is important to increase the thickness of the metal trace and reduce the overall resistance accordingly. Skin depth, as known as the characteristic depth of penetration, is an indicator of attenuation in good conductor. The amplitude of the field in the conductor will decay by 36.8% after travelling a distance of skin depth from the surface into the conductor. The skin depth is defined as

$$\delta_s = \sqrt{\frac{2}{\omega\mu\sigma}} \ , \tag{1}$$

Where ω is the angle frequency, μ is the permeability of the conductor, and σ is the conductivity of the conductor [28]. Skin depth of the inkjet-printed silver conductor which use the NPS-JL NanoPaste® silver ink is about from 3.4 μm to 4.1 μm at 900 MHz when the minimal resistivity is achieved after sintering. The skin depth is usually thicker than the thickness of typical inkjet-printed conductor which may lead to power losses. Thus, multiple layers are important to achieve a better performance.

4.3 Optimization of printing parameters based on printed lines

To test the conductivity performance of the printed patterns on different substrates, simple lines with different layers were firstly printed and tested. The dimension of line pattern fixed on 5mm × 30mm. After sintering, the resistances of these lines were measured by Fluke Model 111 True RMS Multimeter and the surface magnified images were taken from Olympus BX60M Olympus Metallurgical Microscope equipped with Olympus ColorView IIIu camera with a resolution of 2576 × 1932.

4.3.1 Conductivity performance on cardboard

Cardboard is an everyday material, which has a porous surface, thus, ink can be absorbed by the substrate. This absorbing will reduce the conductivity of the printed patterns. In this case, coating of the substrate is applied to improve the conductivity and different coating methods can lead to various performances. This section focuses on the measured resistances of printed lines on cardboard substrate, which are shown in Table 6. More details will be introduced in the following content.

Table 6 Resistances of printed lines on cardboard substrates

Substrate	Total Layer(s)	Resistance	Description
4083/219	1	∞	the edge of line is conductive, mostly black
	2	∞	the edge of line is conductive, mostly black
	4	79 Ω	the edge of line is conductive, mostly black
	6	14 Ω	the edge of line is conductive, mostly black
	8	1.3 Ω	the edge of line is conductive, partially black
	1-S-1	5 Ω	Totally silver, good conductivity
	2-S-2	0.8 Ω	Totally silver, good conductivity
	4-S-4	0.3 Ω	Totally silver, good conductivity
4083/207	2	∞	the edge of line is conductive, mostly black
	4	∞	the edge of line is conductive, mostly black
	6	116 Ω	the edge of line is conductive, mostly black
4083/618	4	2.5 MΩ	bad conductive, absorbed
	8	161 Ω	bad conductive, absorbed
4083/P8	4	26 Ω	bad conductive
	8	12 Ω	bad conductive

First, one-layer lines were printed on double coated cardboard 4083/219 to test the conductivity and these lines were not conductive at all. But from the magnified surface image, it can be observed that the edge of line is metallic while the black central area of the line pattern is dielectric, as shown in Figure 12.

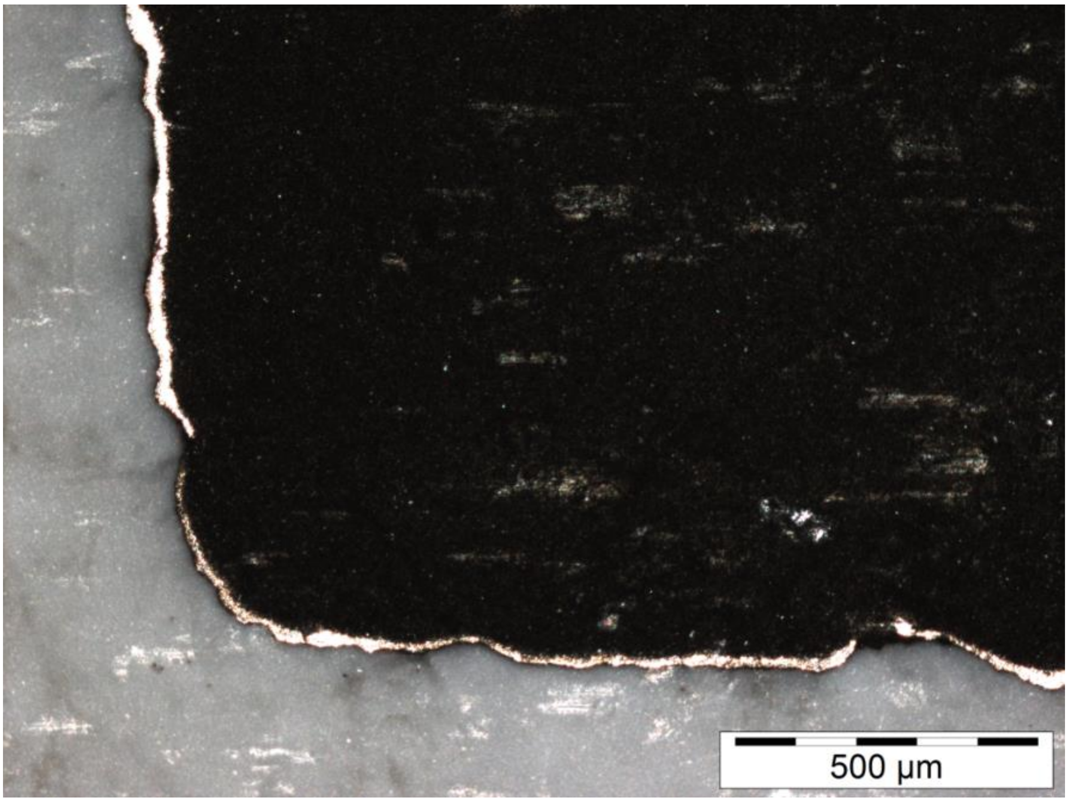

Figure 12 Optical microscope image of one-layer line on cardboard 4083/219

Then lines with multiple layers were printed on this substrate as a comparison. A normal method for fabricating multilayer patterns is printing multiple layers directly before sintering. This method provides sufficient ink on the substrate to freight the printed patterns. Two-layer line also shows no conductivity, but according to Figure 13 from the optical microscope, the metallic area is increased. Furthermore, with four layers, the resistance is 79 Ω although most of parts are still black. Figure 14 shows that larger area of eight-layer line becomes conductive and the resistance is correspondingly lower, which can reach 14 Ω. Based on the analyses above, it is apparent to summarize that the metallic area (silver part from the picture) is increased with the printed layers.

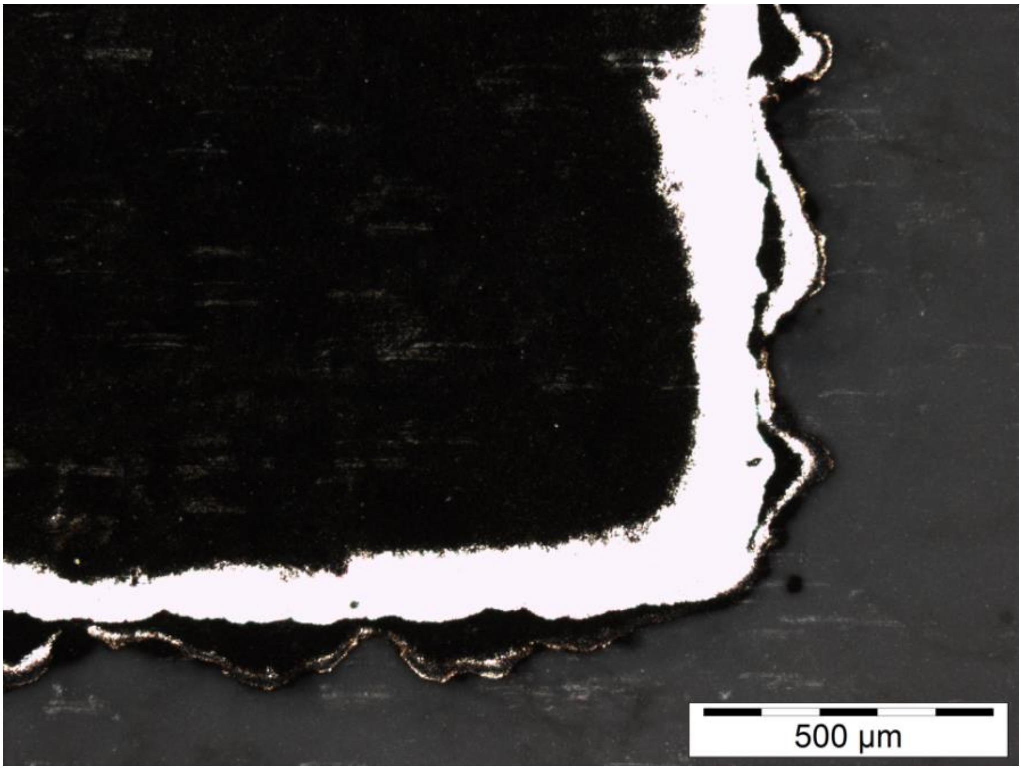

Figure 13 Optical microscope image of two-layer line on cardboard 4083/219

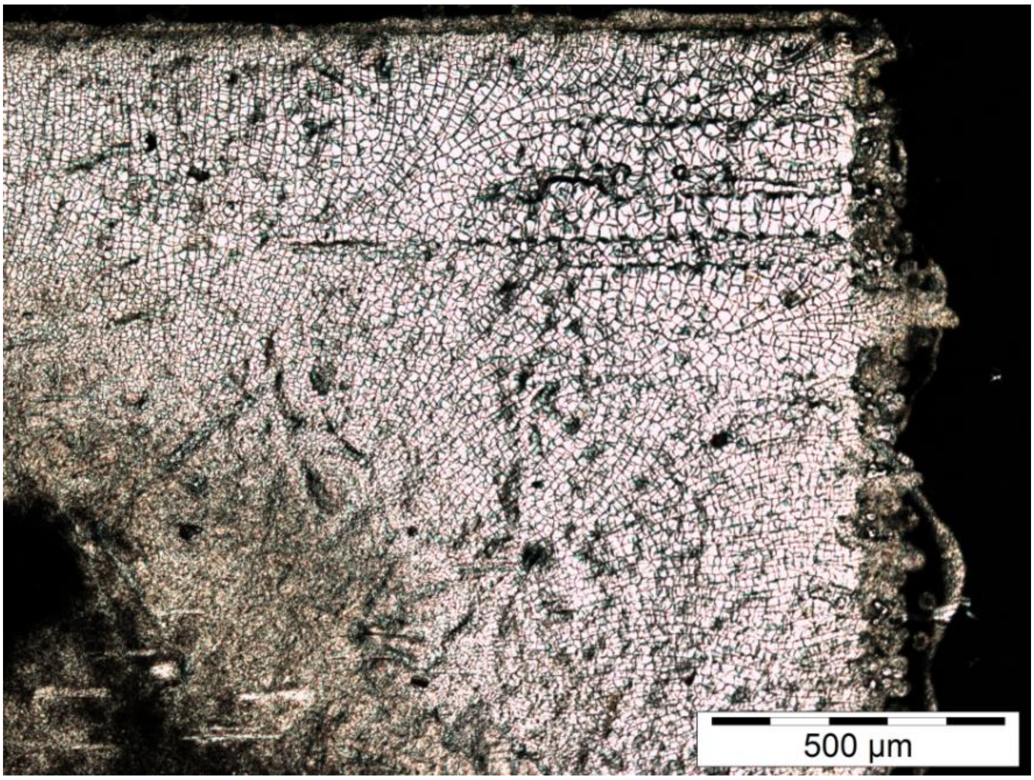

Figure 14 Optical microscope image of eight-layer line on cardboard 4083/219

Another approach to manufacture the pattern with multiple layers is repeating the process of printing and sintering. Based on this way, two printing-sintering rounds were carried out. At each turn, one-layer, two-layer and four-layer lines were printed on the cardboard and sintered with the oven. After that, the average resistance of those lines was measured, which were 5 Ω, 0.8 Ω and 0.3 Ω respectively. Figure 15 shows the surface of the patterns, which print four layers at each round. Compared with the optical microscope image of eight-layer line, this picture shows less gaps and more homogenous surface. But the shortcoming of this method is also obvious, different layers are hard to be aligned perfectly, which will lead to the negative effect, especially when printing tag antennas.

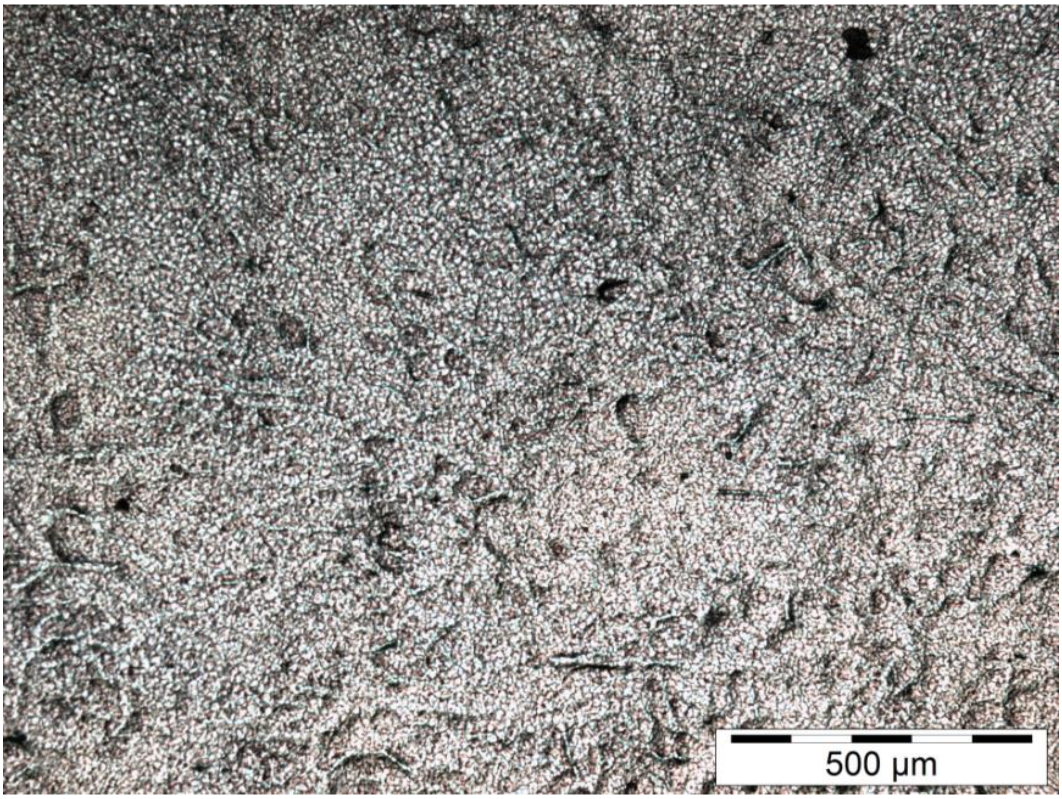

Figure 15 Optical microscope image of 4-s-4 layers line on cardboard 4083/219

As for pre-coated cardboard 4083/207, the characteristic of the printed lines are similar with the cardboard 4083/219. The edge of the printed lines is conductive while the central part is dielectric. But the resistance is partly higher than lines printed on the 4083/219 when the same layers are deposited. Figure 16 is the surface image of the six-layer line.

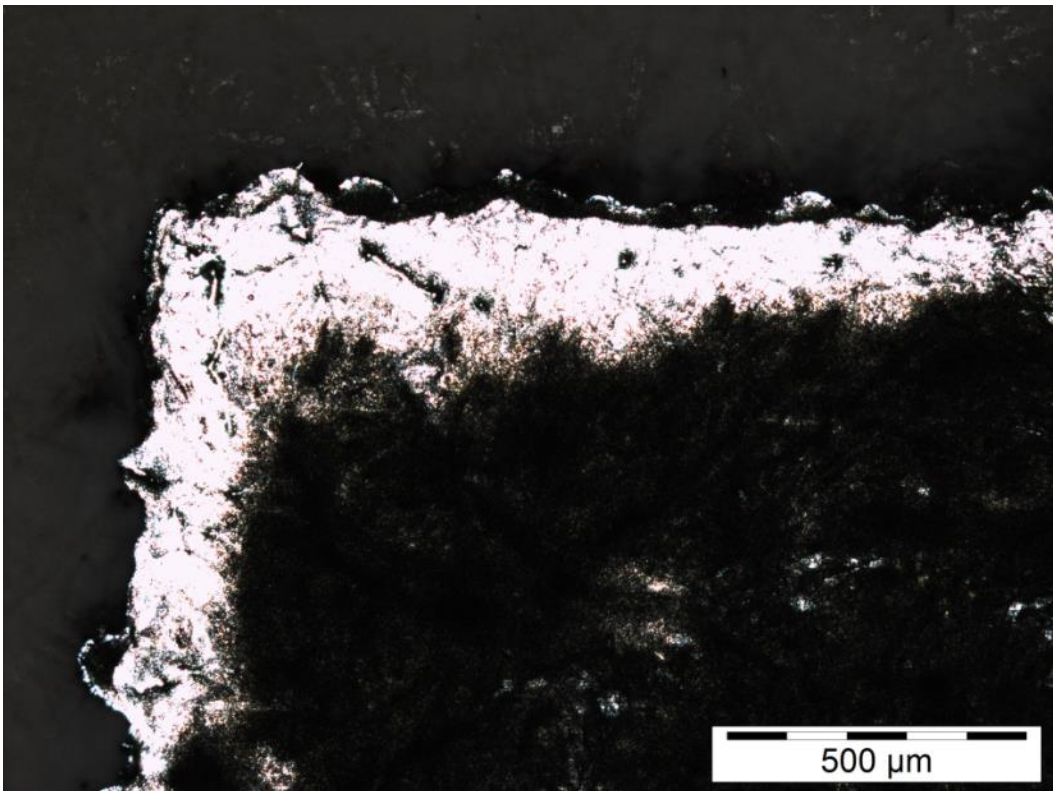

Figure 16 Optical microscope image of six-layer line on cardboard 4083/207

The conductivity of the lines on pre-calendered cardboard 4083/618 is bad, the resistances of four-layer line and eight-layer line are 2.5 MΩ and 161 Ω respectively. Figure 17 shows the surface magnified image of the four-layer line, the ink is absorbed by the substrate and the surface of printed pattern is predominantly black with silver area inside. The metallic parts are not so sufficient to form a good conductive trace, so the resistance is extremely high. As a comparison, Figure 18 shows more silver parts on eight-layer line, which has a lower resistance.

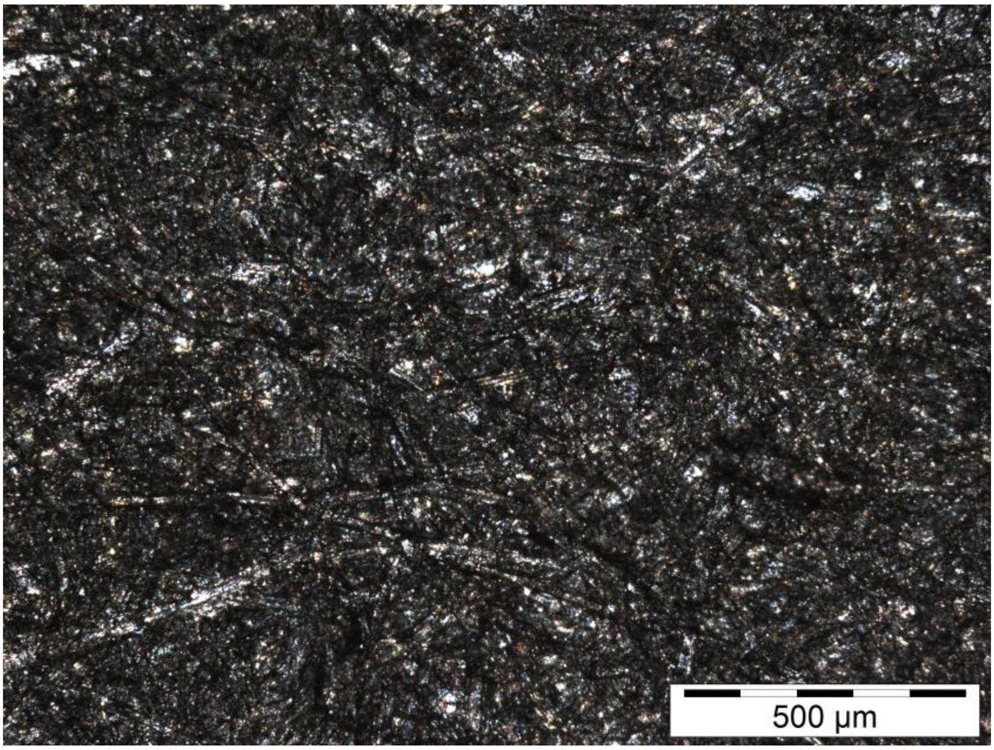

Figure 17 Optical microscope image of four-layer line on cardboard 4083/618

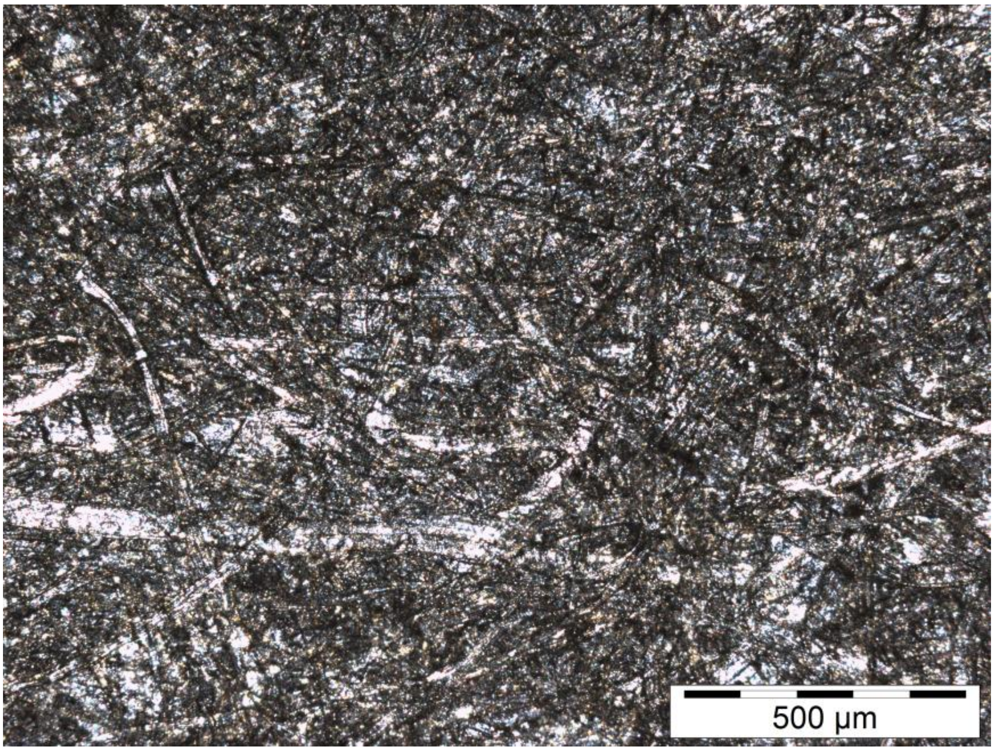

Figure 18 Optical microscope image of eight-layer line on cardboard 4083/618

The conductivity of baseboard 4083/P8 is better than 4083/618, but the average resistances are also not low enough. Figure 19 shows the surface magnified image of eight-layer line, the ink is also absorbed by the substrate. In addition, some inks are spread out at the edge of the pattern since the substrate cannot absorb any more ink.

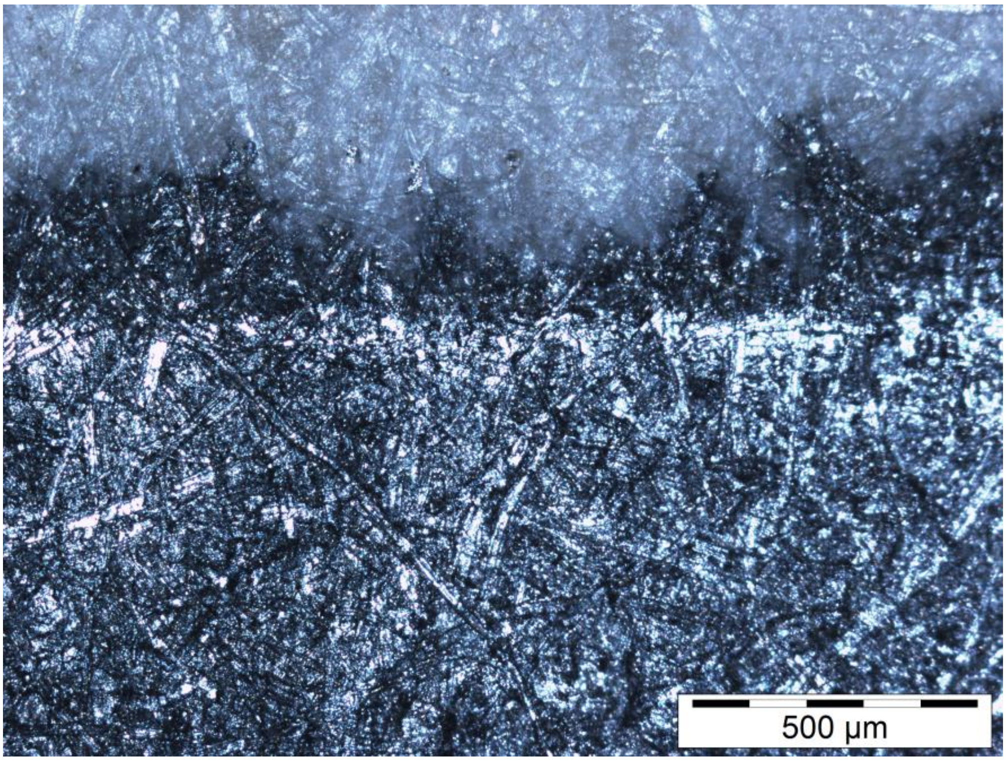

Figure 19 Optical microscope image of eight-layer line on cardboard 4083/P8

4.3.2 Conductivity performance on paper

This section focuses on the measured resistances of printed lines on paper substrates, results are listed in Table 6. More details will be introduced in the following content.

Table 7 Resistances of printed lines on paper substrates

Substrate	layers	resistance	description
4104/P1	1	∞	not conductive, absorbed
	2	∞	not conductive, absorbed
	4	∞	not conductive, absorbed
	8	∞	not conductive, absorbed
4104/648	4	∞	not conductive, absorbed
	8	∞	not conductive, absorbed
4095/413	1	1.8 Ω	good conductivity
	2	0.8 Ω	good conductivity
	4	0.3 Ω	good conductivity
4095/214	2	∞	mostly black
	4	59 Ω	the edge of line is conductive, mostly black
	6	2.1 Ω	good conductivity
4095/204	4	∞	the edge of line is conductive
	8	∞	the edge of line is conductive

On coated and calendered paper 4095/413, one-layer lines obtain good conductivity after sintering. The resistance is 1.8 Ω. As shown in Figure 20, there are lots of black holes and thin gaps on the surface since the ink is deposited row by row from the print head. If the diameter of the ink droplet is less than the distance of narrow rows of deposition, thin gaps and holes will appear. Another possible reason is the inadequacy of the ink when one layer is selected.

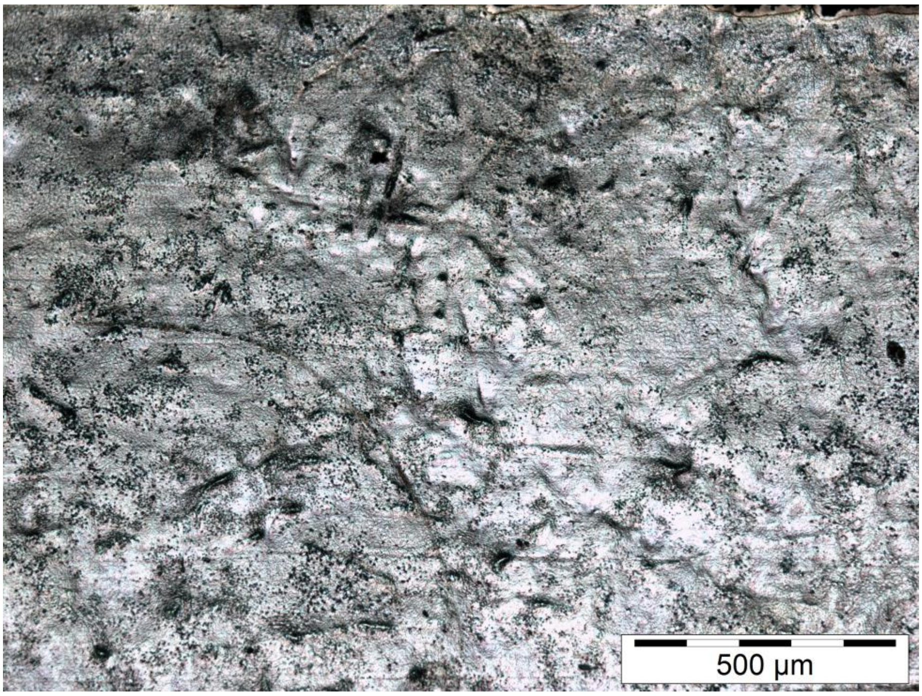

Figure 20 Optical microscope image of one-layer line on paper 4095/413

As printed layers increase, the surface of the printed line becomes more homogenous and less holes and gaps are detected. Thereby, the conductivity of the lines is increased with layers. Surface magnified images of two-layer line and four-layer line are shown in Figure 21 and Figure 22 respectively.

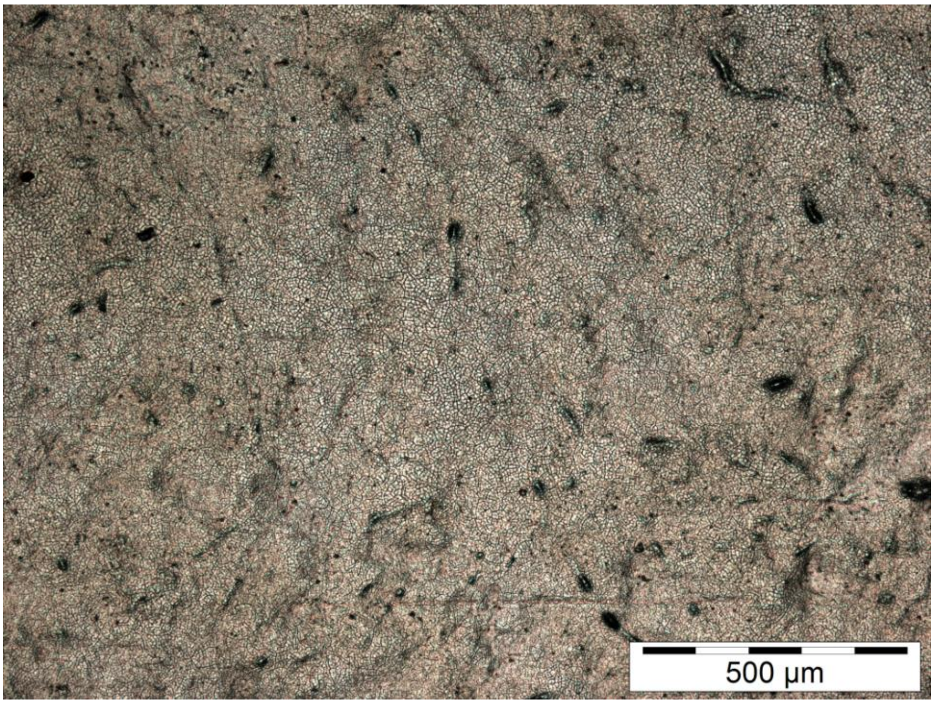

Figure 21 Optical microscope image of two-layer line on paper 4095/413

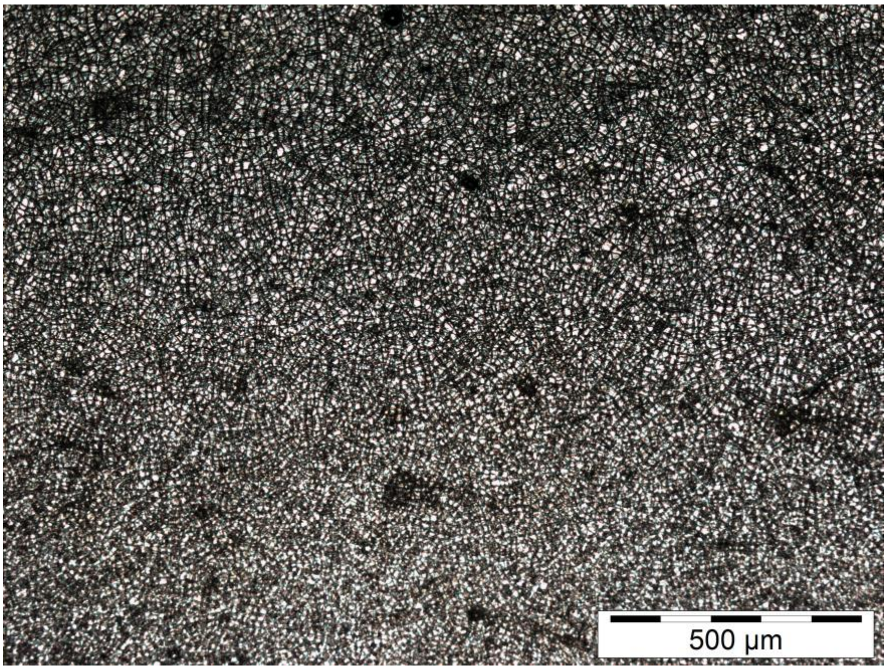

Figure 22 Optical microscope image of four-layer line on paper 4095/413

Two-layer line on double coated paper 4095/214 shows no conductivity and the surface of printed line is mostly black, as shown in Figure 23. As a comparison, the successive metallic part is formed at the edge of the four-layer pattern, which is shown in Figure 24. In addition, similar with the previous substrates, as the layers increase, the area of silver part grows accordingly. Multilayer printing brings much more ink and a greater thickness of silver film therefore results in less resistance.

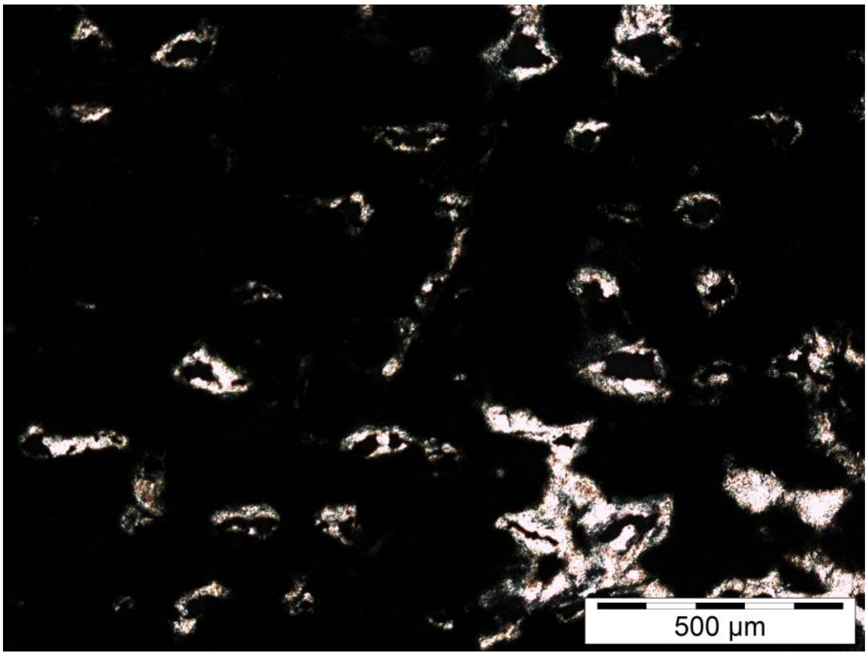

Figure 23 Optical microscope image of two-layer line on paper 4095/214

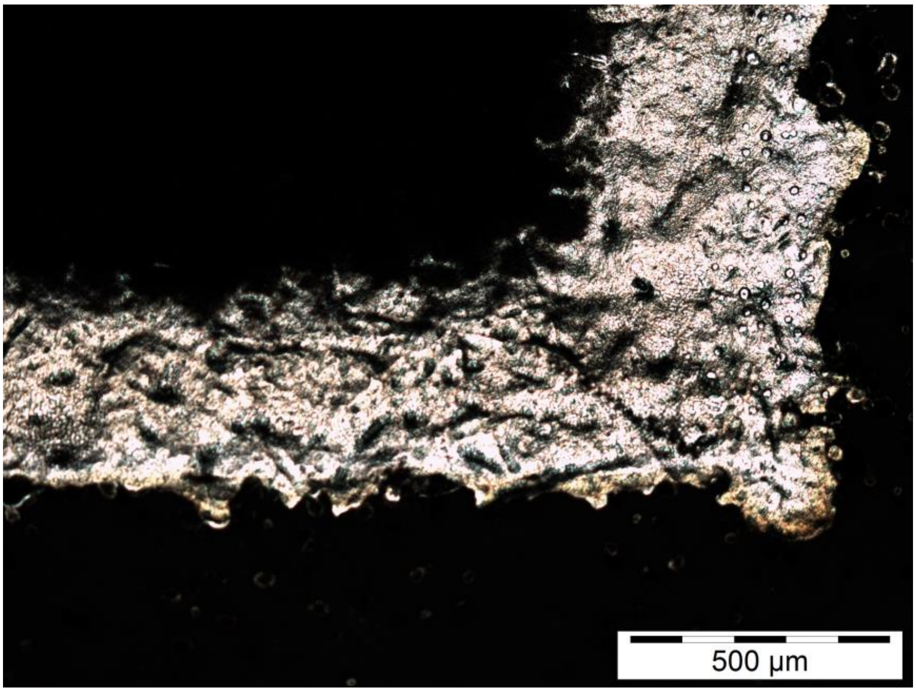

Figure 24 Optical microscope image of four-layer line on paper 4095/214

Similar situation is found when lines were printed on film coated paper 4095/204. Although four-layer and eight-layer lines are nonconductive, there are still narrow silver parts at the edge of the line. Unfortunately, since these silver parts are discontinuous, they are unable to construct an electric trace. Figure 25 shows the corner of the four-layer line pattern.

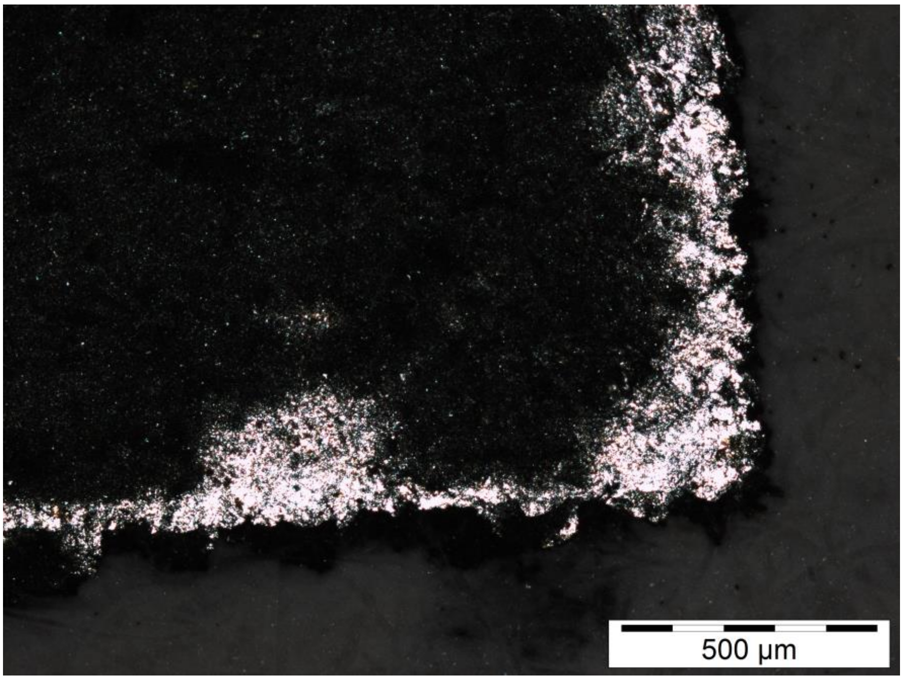

Figure 25 Optical microscope image of four-layer line on paper 4095/204

As for uncalendered paper 4104/P1, two-layer line is dielectric and the surface is not metallized at all, as shown in Figure 26. Depositing four layers directly does not provide any improvement that the surface is still mostly black, which is depicted in Figure 27.

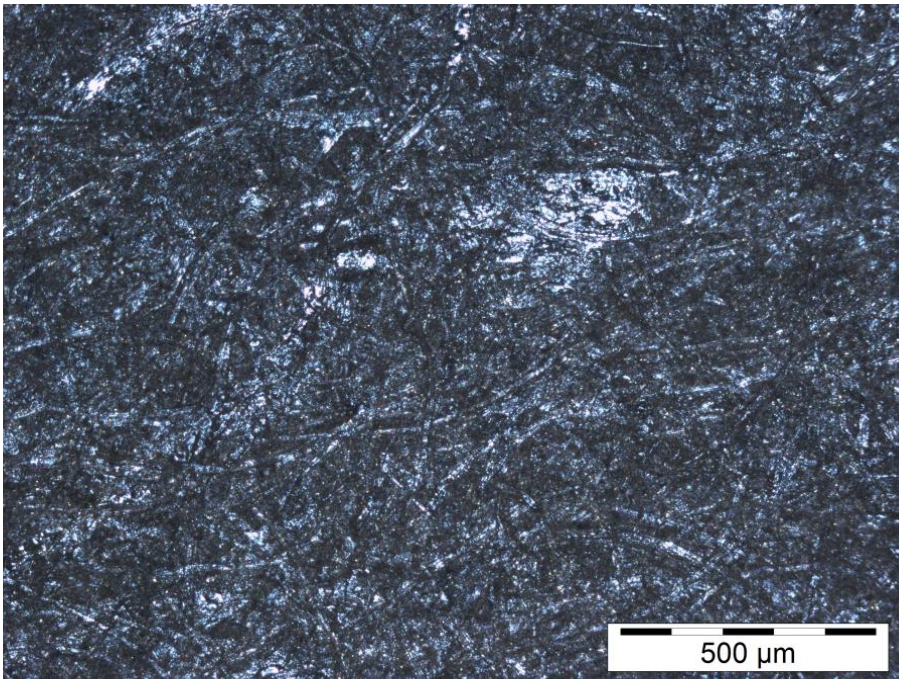

Figure 26 Optical microscope image of two-layer line on paper 4104/P1

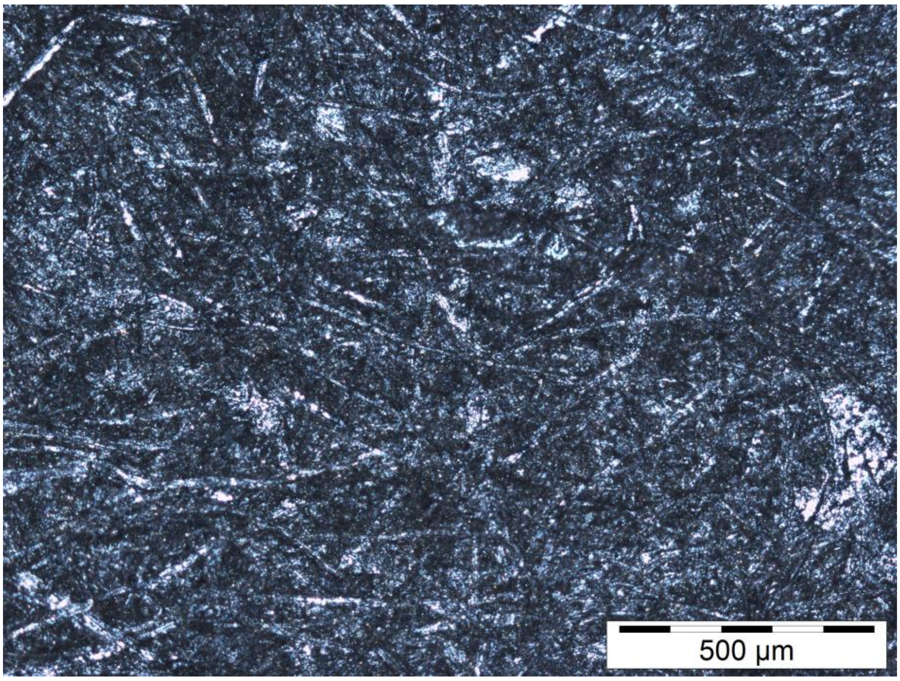

Figure 27 Optical microscope image of four-layer line on paper 4104/P1

Similar with the previous one, lines on uncoated paper 4104/648 also shows no conductivity. The surface of four-layer line is mostly black and no coherent metallic trace formed after sintering, as shown in Figure 28.

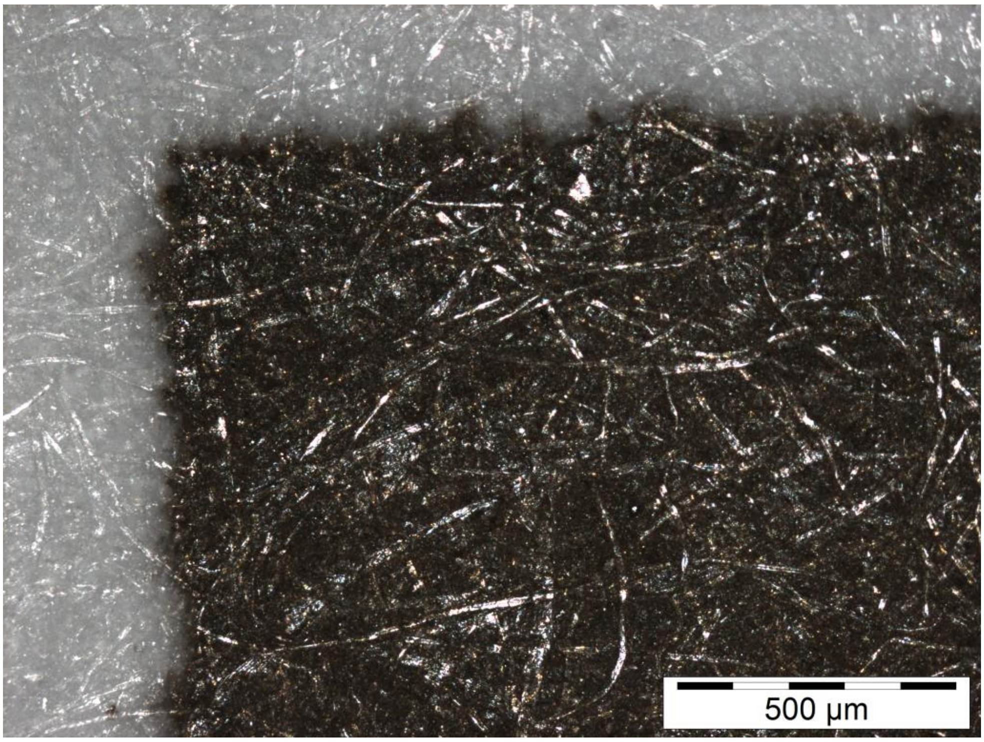

Figure 28 Optical microscope image of four-layer line on paper 4104/648

5. RFID TAGS MEASUREMENT AND RESULTS

5.1 Inkjet-printed UHF RFID antennas

As a typical Passive UHF RFID tag antenna, the compact dipole-type structure is designed for inkjet printing, which is shown in Figure 29. This antenna is supposed to optimum matching with Alien Technology Higgs-3 RFID IC at 900MHz [29].

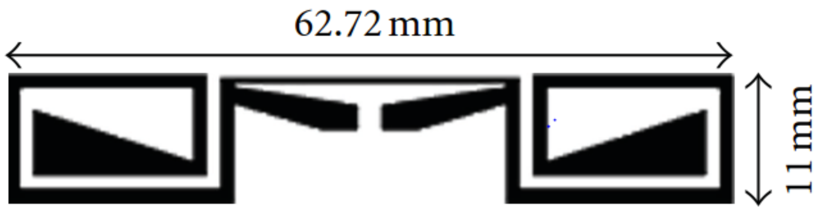

Figure 29 UHF RFID tag antenna layout [29].

Based on previous measurement, paper substrate 4104/P1 and 4104/648 did not have any possibility to form conductive printed trace, so in the following chapter, passive UHF RFID tag antennas were printed on these substrates: 4095/413, 40957214, 4095/204, 4083/219, 4083/207, 4083/P8 and 4083/618. After the antennas were printed and sintered, Alien Technology Higgs-3 RFID ICs were attached to them with CW2400 Conductive Epoxy from CircuitWorks® [30].

5.2 RFID tag measurements and results

After fabrication, these inkjet-printed passive UHF RFID tags were measured in Voyantic Tagformance lite system in an anechoic RFID measurement cabinet [31]. As a bistatic reader, Tagformance works with output power from 3 dBm to 27.8 dBm and sensitivity of -80 dBm. During the measurement, tags were placed 40 cm away from the reader antenna that interrogates the tag across 800 to 1000 MHz with a frequency step of 1MHz. Tagformance measured the read range at the minimum power which is necessary to active the IC of tags.

Voyantic wideband UHF reference is applied to calibrating every time before the tag measurement [31]. By characterizes the measurement environment, calibration can allow the software to calculate the theoretical read range in the forward direction given by

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{\tau G_{tag} EIRP}{P_{ic,0}}}, with\ \tau = \frac{4\, Re(Z_{tag})\, Re(Z_{ic})}{|Z_{tag}+Z_{ic}|^2} \quad (2)$$

Where G_{tag} is the tag antenna gain in the forward direction, EIRP is the equivalent istropically radiated power, and τ is the power transmission coefficient between the tag antenna and tag chip. Z_{tag} and Z_{ic} is the impedances of tag antenna and tag chip respectively. The read sensitivity $P_{ic,0}$ of Alien Technology Higgs-3 RFID IC is -18 dBm [32].

5.2.1 RFID tag measurements of paper substrate

The read ranges of inkjet-printed tags on paper substrate 4095/413 are shown in Figure 30.

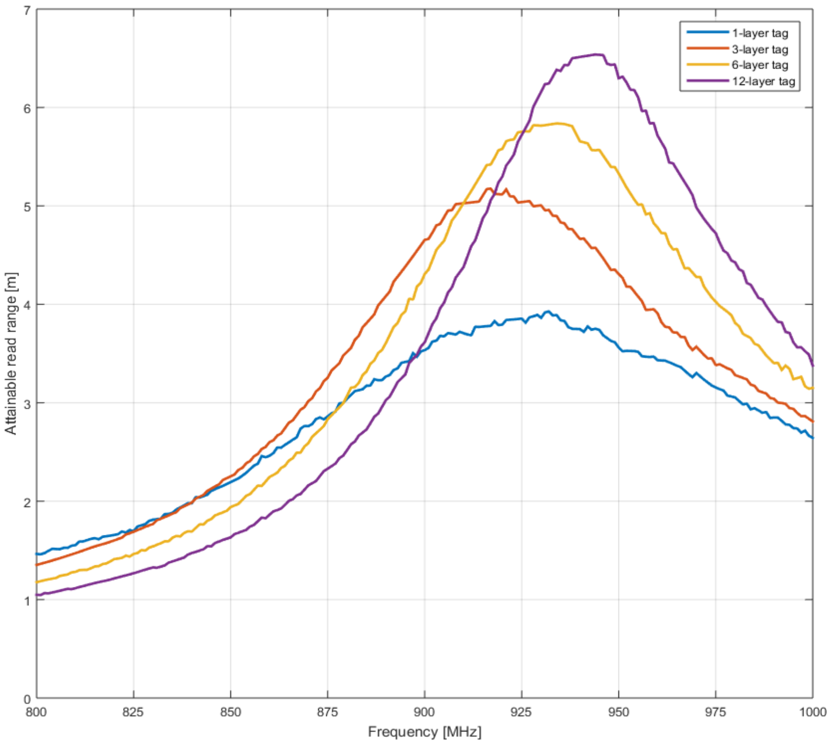

Figure 30 Read ranges of inkjet-printed tags on paper 4095/413

Based on Figure 30, the peak read ranges of those tags with different layers on 4095/413 are listed in Table 7.

Table 8 Peak read ranges of tags on paper 4095/413

Substrate	Layers	Peak read range (m)
4095/413	1	3.8
	3	5.1
	6	5.8
	12	6.5

Theoretically, on this paper substrate, more layers lead to longer read range since more ink is deposited on paper to form conductive pattern. Based on previous chapter, thicker conductor has lower losses and better radiation efficiency, which can obtain longer read range.

Figure 31 shows the read ranges of multilayer tags on paper substrate 4095/214. Firstly, it indicates the same tendency that the read ranges are increased with layers. But then, the read ranges of 12-layer tag are lower than 8-layer tags which have best performance. Peak read ranges of different tags are listed in Table 8. In conclusion, when deposit multiple layers directly, more layers are not always corresponding to higher read range, the optimized layers of every substrate can be obtained during the experiment.

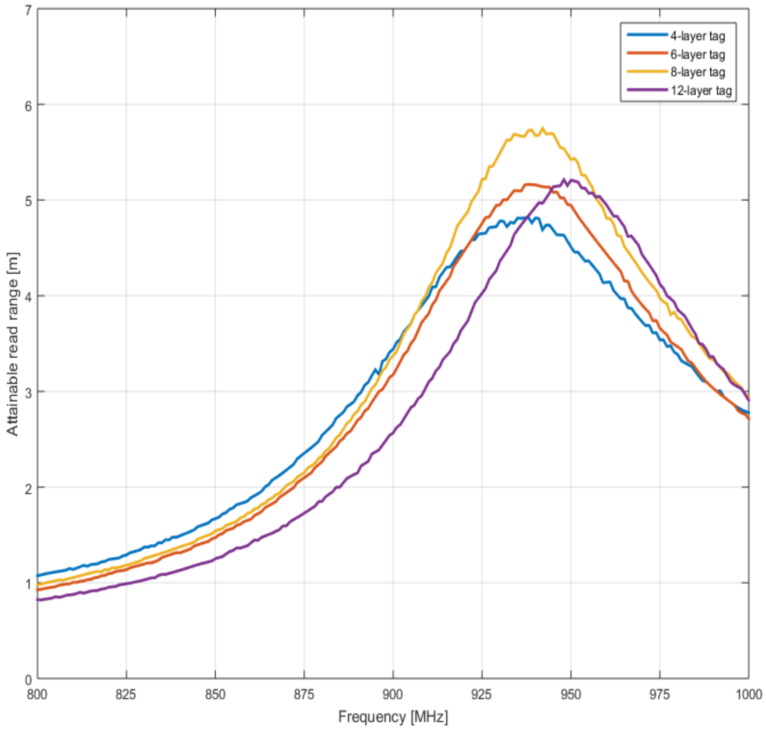

Figure 31 Read ranges of inkjet-printed tags on paper 4095/214

Table 9 Peak read ranges of tags on paper 4095/214

Substrate	Layers	Peak read range (m)
4095/214	4	4.8
	6	5.2
	8	5.8
	12	5.3

According to the measurement before, the four-layer line on paper 4095/204 shows no conductivity but narrow metallic parts can be formed at the edge of the printed pattern. When eight layers were deposited, the silver parts are increased correspondingly.

In regard to tag measurement, four-layer tags respond nothing when put them into the Voyantic Tagformance lite system. In addition, the peak read ranges of 8-layer and 12-layer tags are 5 m and 6.1 m respectively. Figure 32 indicates theoretical read ranges of tags on paper 4095/204 and peak read ranges are listed in Table 9.

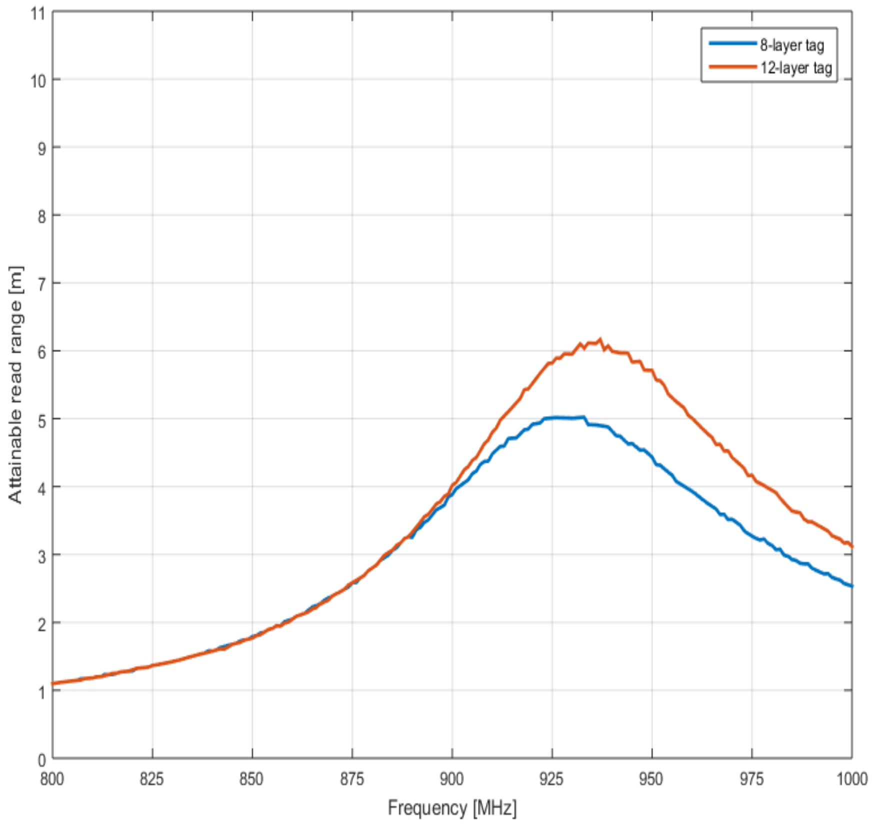

Figure 32 Read ranges of inkjet-printed tags on paper 4095/204

Table 10 Peak read ranges of tags on paper 4095/204

Substrate	Layers	Peak read range (m)
4095/204	0	0
	8	5
	12	6.1

5.2.2 RFID tag measurements of cardboard substrate

Double coated cardboard 4083/219 is also a practical substrate for inkjet printing using siver nanoparticle ink. Based on Figure 33, which shows the theoretical read ranges of tags on cardboard 4083/219, 6-layer tag has best performance and the peak read range can reach 6.1 m. After that, when more layers are printed, the read range is decreased inversely. Peak read ranges of all tags are listed in Table 10.

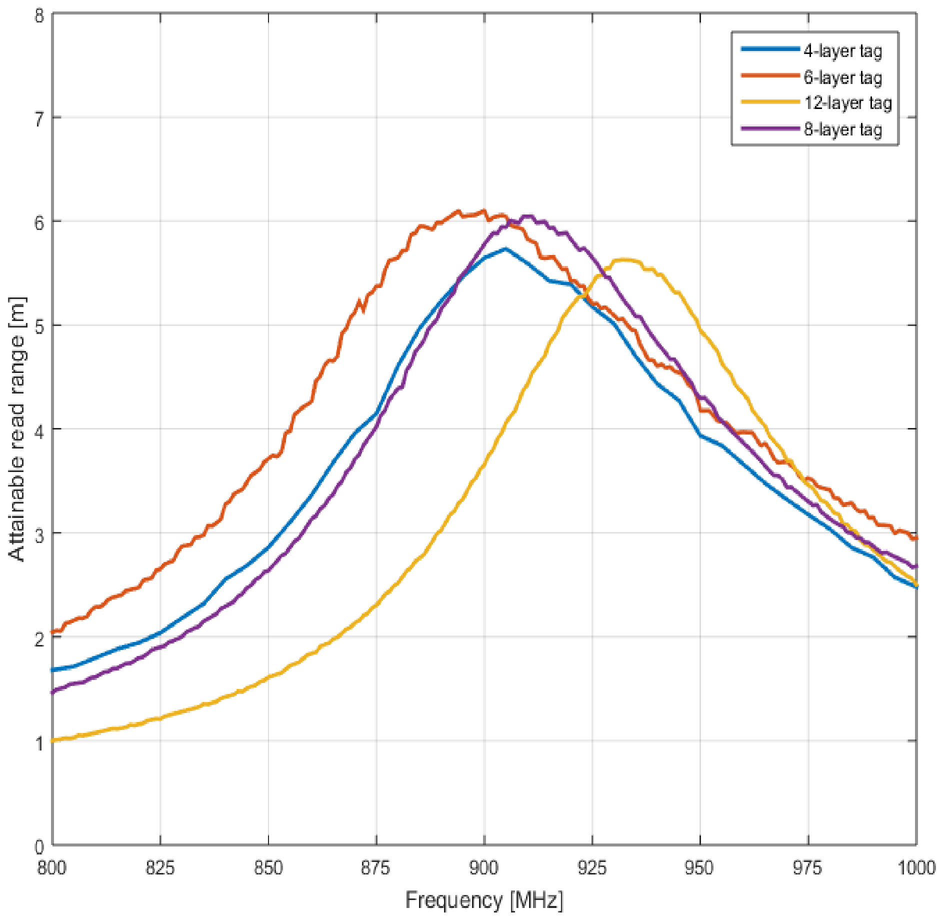

Figure 33 Read ranges of inkjet-printed tags on cardboard 4083/219

Table 11 Peak read ranges of tags on cardboard 4083/219

Substrate	Layers	Peak read range (m)
4083/219	4	5.7
	6	6.1
	8	6
	12	5.6

When fabricated tags on cardboard 4083/207, two methods were used to deposit multiple layers. One method is printing multiple layers directly before sintering. Based on this way, the peak read range of 4-layer tag is 1.7 m. In contrast, another method was applied to printing 4-layer tags. We repeated the process of printing and sintering two times and two layers were printed at each turn. In this case, the peak read range can reach 3 m which is much higher than the previous one. But there are also some shortcomings of this method, such as misalignment between different layers and time consuming. Thus, When fabricated tags with more layers, directly printing leads to better performance than repeating printing and sintering process since it can simplify the manufacturing process and eliminate the misalignment. As a result, directly printed 8-layer tags have best read range. The read ranges of inkjet-printed tags on 4083/207 are shown in Figure 34, and all peaks are listed in Table 11.

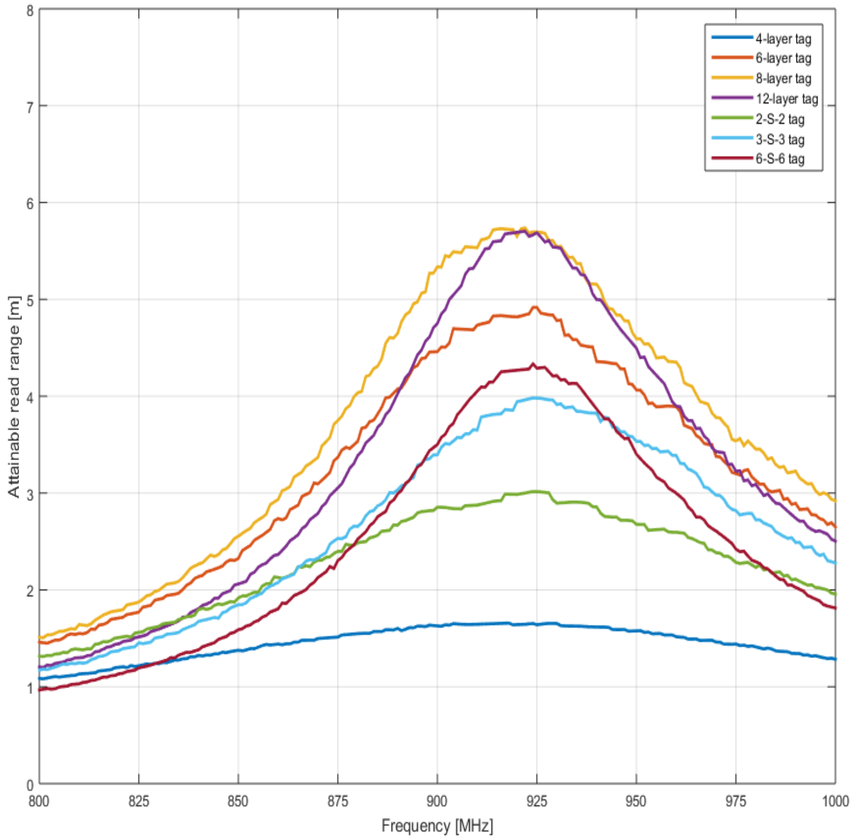

Figure 34 Read ranges of inkjet-printed tags on cardboard 4083/207

Table 12 Peak read ranges of tags on cardboard 4083/207

Substrate	Layers	Peak read range (m)
4083/207	4	1.7
	6	4.8
	8	5.7
	12	5.7
	2-S-2	3
	3-S-3	4
	6-S-6	4.3

During the conductivity measurement, the resistances of printed lines on cardboard 4083/618 are very high. Thus, the performance of tags on this substrate is unsatisfying. The read ranges of inkjet-printed tags on 4083/618 are shown in Figure 35, and all peaks are listed in Table 12. Eight layers were firstly deposited directly for measuring and the peak read range is only 2 m. Next, 12-layer tags were manufactured by repeating printing and sintering process two times, and 6 layers were deposited at each round. The peak read range can reach 4 m, which is sufficient for many applications although longer read range is expected.

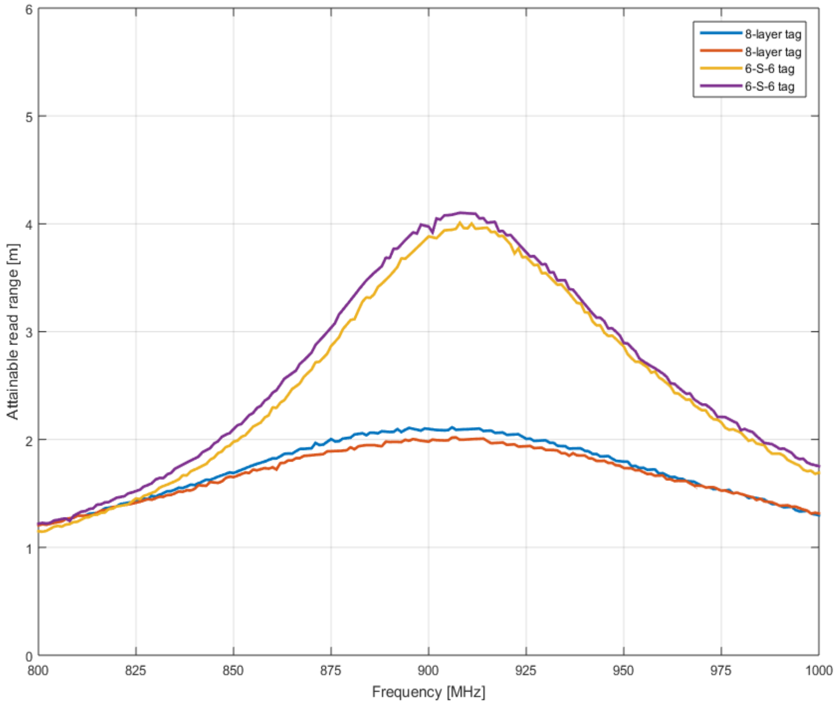

Figure 35 Read ranges of inkjet-printed tags on cardboard 4083/618

Table 13 Peak read ranges of tags on cardboard 4083/618

Substrate	Layers	Peak read range (m)
4083/618	4	0
	8	2.2
	6-S-6	4.1

Similar with cardboard 4083/618, cardboard 4083/P8 also has bad conductivity, thus, theoretical read ranges of inkjet-printed tags are also not good, which is shown in Figure 36. The peak read ranges of all tags on 4083/P8 are listed in Table 13. As a result, longest peak read range among all tags is around 3.7 m.

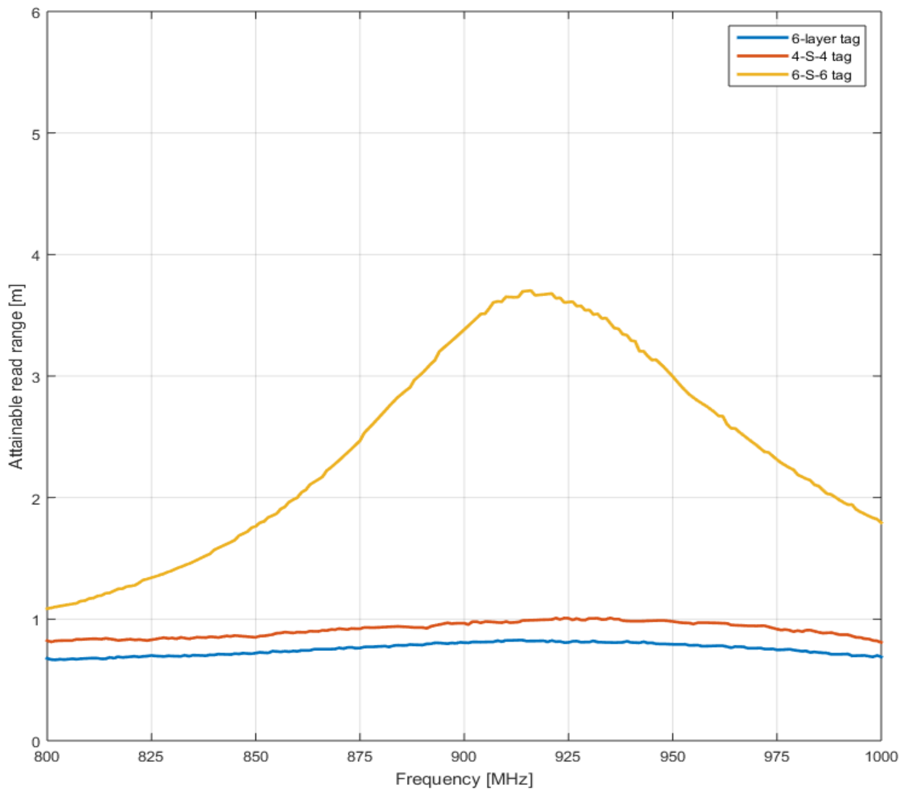

Figure 36 Read ranges of inkjet-printed tags on cardboard 4083/P8

Table 14 Peak read ranges of tags on cardboard 4083/P8

Substrate	Layers	Peak read range (m)
4083/P8	6	0.8
	4-S-4	1
	6-S-6	3.7

6. CONCLUSION

The aim of this thesis is to study the possibility of inkjet printing on paper-based substrates using silver nanoparticle ink and to optimize the printing parameters for fabricating passive UHF RFID tags on these substrates. A simple line pattern with dimension of 5mm × 30 mm was printed on these substrates to evaluate the conductivity and surface magnified images from the optical microscope were taken to analyze the performance.

Two methods were applied to depositing multiple layers. One approach is to directly print multilayers before sintering, and another one is to repeat printing and sintering process several times. Since second method has shortcomings like time-consuming and misalignment between different layers, the first method was utilized in most cases.

The silver nanoparticle ink cannot be sintered on paper 4104/P1 and 4104/648 due to the ink absorption. The surface of the printed lines on both two substrates is mostly black. In contrary, conductivity performance on other substrates is various. Thus, RFID tags were fabricated on these substrates and the read ranges were measured by using Voyantic Tagformance lite system.

Paper 4095/413 is the best substrate for inkjet printing using the silver nanoparticle ink. The surface of printed pattern on this substrate is the most homogeneous and totally silver. In addition, the printed tags on this paper substrate have the highest read range. The peak read range of the 12-layer tag can reach 6.5 m. But in consideration of the fabrication time and the cost, 4 layers are sufficient for most applications. Directly printed tags on paper 4095/204 have similar performance with 4095/413 but the read ranges are shorter. The 12-layer tag is the best choice for this substrate and the peak read range is 6.1 m. As for cardboard 4083/219, cardboard 4083/207 and paper 4095/214, the 8-layer tag has best performance, the peak read ranges are 6 m, 5.7 m and 5.8 m respectively. More layers will lead to lower read ranges inversely. Using the first depositing method, the read ranges of multilayer tags on cardboard 4083/P8 and cardboard 4083/618 are unsatisfied. Thus, tags were fabricated by repeating printing and sintering process two times, and 6 layers were deposited at each turn. As a result, the peak read ranges of the 6-S-6 tags on 4083/P8 and 4083/618 can reach 3.7 m and 4.1 m respectively which are sufficient for normal usage. As a conclusion, specific printing parameters especially layers are necessary for each substrate.

In the future research, copper nanoparticle ink and IPL sintering on these paper-based substrates will studied as a comparison.

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