



**AIN SHAMS UNIVERSITY**  
**FACULTY OF ENGINEERING**  
**Electronics and Communications Engineering Department**

# **RF Components Using Nanoparticles**

A Thesis

**Submitted in partial fulfillment of the requirements of the degree of**  
**Doctor of Philosophy in Electrical Engineering**  
(Electronics and Communications Engineering)

Submitted by:

**Shaimaa Ali Mohammed Beeh Mohassieb**

**M.Sc. in Electrical Engineering**  
(Electronics and Communications Engineering)  
**Ain Shams University**

Supervised By

**Prof. Hadia Mohammed Said El-Hennawy**  
**Prof. Khaled Abdelwahab Kirah**

Cairo 2017



**AIN SHAMS UNIVERSITY**  
**FACULTY OF ENGINEERING**  
**Electronics and Communications Engineering Department**

# **RF Components Using Nanoparticles**

Submitted by:

**Shaimaa Ali Mohammed Beeh Mohassieb**

**M.Sc. in Electrical Engineering**  
**(Electronics and Communications Engineering)**  
**Ain Shams University, 2010**



**AIN SHAMS UNIVERSITY**  
**FACULTY OF ENGINEERING**  
**Electronics and Communications Engineering Department**

**Examiners Committee**

**Name:** Shaimaa Ali Mohammed Beeh Mohassieb  
**Thesis:** RF Components Using Nanoparticles  
**Degree:** Doctor of Philosophy in Electrical Engineering  
(Electronics and Communications Engineering)

**EXAMINERS COMMITTEE**

<b>Name</b>	<b>Signature</b>
<b>Prof. Esmat Abdel-Fattah Abdallah</b> Microstip Department, Electronics Research Institute	.....
<b>Prof. Hani Amin Ghali</b> Ain Shams University, Faculty of Engineering, Electronics and Communications Engineering Dept.	.....
<b>Prof. Hadia Mohamed Said El-Hennawy</b> Ain Shams University, Faculty of Engineering, Electronics and Communications Engineering Dept.	.....
<b>Prof. Khaled Abdelwahab Kirah</b> Ain Shams University, Faculty of Engineering, Engineering Physics and Mathematics Dept.	.....

Date: .... / ..... / 2017

# STATEMENT

This dissertation is submitted to Ain Shams University in partial fulfillment for the degree of Doctor of Philosophy in Electrical Engineering (Electronics and Communications Engineering), 2017.

The work included in this dissertation was carried out by the author at the Electronics and Communications Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis was submitted for a degree or a qualification at any other university or institution.

**Name:** Shaimaa Ali Mohammed Beeh Mohassieb

**Signature:**

**Date:**

# Researcher Data

Name	: Shaimaa Ali Mohammed Beeh Mohassieb
Date of birth	: June, 10, 1983
Place of birth	: Cairo, Egypt
Academic Degree	: M.Sc. in Electrical Engineering
Field of specialization	: Electronics and Communications Engineering
University issued the degree	: Faculty of Engineering, Ain Shams University
Date of issued degree	: March, 2010
Current job	: Assistant lecturer at Akhbar Elyom Academy in Egypt

# ACKNOWLEDGMENT

All gratitude is due to “ALLAH” who guides me to bring forth to light this thesis.

I would like to thank many people for their help and encouragement in completing my thesis.

Thanks, are first due to Prof. Hadia El-Hennawy, for her understanding, patience, encouragement, besides, overcoming any obstacles that might interfere with my work.

My foremost appreciation goes to Prof. Khaled Kirah. He guided me in every way he could to complete this thesis. Without his encouragement, the thesis could not reach to this level.

Also, my deepest gratitude and sincerest thanks to Dr. Ahmed Khalil, Faculty of Science, Fayoum University, for his supervision, fruitful guidance through the course of the work, encouragement, endless help and many illuminating discussions.

The experimental work in this thesis is part of “SURSYS” project funded by the German Academic Exchange Service (DAAD) and financed by the “Federal Foreign Office”. The author acknowledges the valuable support of Prof. Edgar Dörsam and all the team at the Institute of printing Science and Technology, Technical university of Darmstadt, Germany, for providing the necessary material resources.

Finally, I would like to thank Dr. Ayman Eltager, Military Technical Collage, for his great assistance during antenna’s radiation pattern measurements.

Last, but not least thanks are also due to my family, father, mother and sisters for the love and support that they have given me during their life time.

# ABSTRACT

Inkjet printing is a low-cost technique suitable to fabricate flexible electronic devices using solutions of conductive nanoparticles on a large variety of substrates without material waste as in conventional etching techniques. In this dissertation, low-profile wideband coplanar waveguide-fed monopole antennas operating at 20 GHz are designed and printed using Copper Oxide and Silver nanoparticles inks on flexible substrates. Polyethylene Terephthalate and Epson paper were the chosen flexible substrates. The effects of altering the drop spacing of the ink on the conductivity of the printed films as well as on the antenna parameters were fully investigated by numerical simulations and by measurements. A conductivity of  $2.8 \times 10^7 \Omega^{-1} \text{m}^{-1}$  was found for the Copper Oxide nanoparticles films printed on Polyethylene Terephthalate using a drop spacing of 20  $\mu\text{m}$  leading to superior antenna performance with an achieved gain and efficiency of 1.82 dB and 97.6%, respectively. On the other hand, antennas on Epson paper substrate show a -10 dB return loss, bandwidth which extends from 17.9 GHz up to 23.3 GHz, leading to a fractional bandwidth of 26.0%.

Thin films printed using Silver nanoparticles on Polyethylene Terephthalate substrate have shown a conductivity of  $1.8 \times 10^7 \Omega^{-1} \text{m}^{-1}$  using a drop spacing of 30  $\mu\text{m}$ . The corresponding coplanar waveguide feed monopole antennas achieved a gain and efficiency of 1.67 dB and 96%, respectively. In addition, the size reduction reached 99% relative to bulk material. Experiments showed that smaller drop spacings lead to bulging of the printed lines while the antenna performance decreases for longer ones. At the same drop spacing, antennas printed on Epson paper substrate showed a -10 dB return loss bandwidth which extends from 17.18 GHz up to 24.3 GHz, leading to a fractional bandwidth of 34.34 %.

**Keywords:** Inkjet printing, Silver nanoparticles, Copper oxide nanoparticle ink, Drop spacing, Coplanar waveguide monopole antenna, Conductivity.

## Table of Contents

ACKNOWLEDGMENT.....	V
ABSTRACT.....	VI
Table of Contents.....	VII
List of Figures .....	X
List of Tables .....	XIII
List of Abbreviations .....	XIV
List of Symbols .....	XV
Publications.....	XVI
Chapter 1 : Introduction .....	1
1.1 An Overview .....	1
1.2 Nano-Thin Film Antennas .....	3
1.3 Nanotechnology Instruments .....	4
1.4 Benefits of Nanotechnology in Antenna Advancement.....	4
1.5 Impact and Implications.....	5
1.6 Thesis Organization .....	5
1.7 Thesis Navigation .....	6
Chapter 2 : State-of-the-Art Manufacturing.....	7
2.1 Printing Techniques .....	7
2.1.1 Flexography Printing .....	8
2.1.2 Offset Lithography Printing.....	8
2.1.3 Gravure Printing.....	9
2.1.4 Screen Printing.....	10
2.1.5 Inkjet Printing .....	10
2.1.5.1 Drop Spacing .....	12
2.2 Ink and substrates.....	14
2.2.1 Nanoparticle inks .....	14
2.2.2 Substrates .....	15
2.3 Sintering.....	16
2.4 Material Characterizations .....	17
2.4.1 Conductivity characterization .....	17
2.4.2 Thickness characterization.....	18
Chapter 3 : RF Components Utilizing Nanoparticles by Inkjet Printing Technology:	
Review.....	19



3.1 Introduction.....	19
3.2 Antennas .....	19
3.2.1 CPW-FED antenna at 2.45 GHz using inkjet printing based on Silver nanoparticles on PET as a flexible and wearable substrate .....	19
3.2.2 A compact dual-band antenna based on Polyimide for wearable and flexible telemedicine devices .....	20
3.2.3 Optimized inkjet fractal printed monopole antennas on wearable substrates for BAN systems .....	20
3.2.4 Printed antenna for 1.8 GHz applications based on silver nanoparticles.....	21
3.2.5 Tri-band U-slot monopole antenna inkjet-printed based on paper for wireless applications .....	22
3.2.6 A CPW-Fed inkjet-printed dipole antenna at 60 GHz based-flexible plastic for ISM applications .....	22
3.2.7 A UWB-LPDA antenna inkjet-printed on paper substrate with high gain .....	23
3.3 Wideband antenna by using miniaturized AMC wearable inkjet-printed for sub-GHz applications .....	24
3.4 A 2.4 GHz RF energy harvester inkjet-printed on bulk cardboard substrate.....	24
3.5 Evaluation of microstrip lines inkjet-printed based on silver nanoparticle for RF and microwave applications .....	25
3.6 Inkjet printing of passive microwave circuitry .....	25
3.7 A 17 GHz inkjet printed filter based on silver nanoparticle .....	26
3.8 New -3dB wide band inkjet printed branch-line coupler.....	27
3.9 An ultra-RFID tag with 1.67 Gbps data rate using low-cost inkjet printing on paper substrate .....	27
Chapter 4 : Effect of silver nanoparticle ink drop spacing on characteristics of coplanar waveguide monopole antennas printed on flexible substrates .....	28
4.1 Introduction.....	28
4.2 Design of the coplanar monopole antenna.....	29
4.2.1 Coplanar monopole antenna on Polyethylene Terephthalate substrate .....	29
4.2.2 Coplanar monopole antenna on Epson paper substrate .....	30
4.3. Experimental.....	30
4.4 Results and Discussions.....	32
4.4.1 Characterization of the printed thin films .....	33
4.4.1.1 Thickness measurements.....	33
4.4.1.2 Material characterization .....	34
4.4.2 Antenna characterization .....	36
4.4.2.1 Antenna $S_{11}$ parameter .....	36

4.4.2.2 Other antenna parameters .....	38
4.4.2.3 Radiation patterns.....	39
Chapter 5 : Inkjet printing of a 20 GHz coplanar waveguide monopole antenna using copper oxide nanoparticles on flexible substrates: effect of drop spacing on antenna performance .....	41
5.1 Introduction.....	41
5.2 Experimental .....	41
5.2.1 Printing conditions .....	41
5.2.2 Photo sintering .....	42
5.2.3 Antenna design and printing .....	44
5.3. Results and Discussion .....	45
5.3.1 Drop spacing effect .....	45
5.3.2 Antenna parametric study .....	48
5.3.3 Antenna radiation patterns .....	51
Chapter 6 : Conclusions and Suggestions for Further Work.....	53
6.1 Conclusions.....	53
6.2 Suggestions for Further Work.....	53
REFERENCES .....	55
Appendix I .....	69
Design Equations of Coplanar Lines .....	69

## List of Figures

Figure 1.1: Nanotechnology applications .....	1
Figure 1.2: Properties of Nano-features .....	2
Figure 1.3: Nano-antenna using nanomaterials .....	3
Figure 2.1: Comparison of standard and printed manufacture process .....	7
Figure 2.2: A schematic of flexography printing .....	8
Figure 2.3: Offset lithography printing schematic .....	9
Figure 2.4: A schematic of gravure printing .....	9
Figure 2.5: Screen printing schematics a) flatbed printing, and b) roll-to-roll printing .....	10
Figure 2.6: Inkjet printing schematic setup.....	11
Figure 2.7: Classification of the different inkjet printing technologies .....	11
Figure 2.8: Photograph of the Fujifilm Dimatix Materials Printer 2800 .....	12
Figure 2.9: Schematic presentation of DOD piezoelectric inkjet printing process.....	12
Figure 2.10: The sabre angle's effective effect on the drop spacing.....	13
Figure 2.11: Printed lines morphologies based on Silver Nanoparticles (SNPs) ink using inkjet printer.....	15
Figure 2.12: Printed electronic on Polyethylene Terephthalate flexible substrate using printing techniques.....	16
Figure 2.13: Novacentrix PulseForge 1200 photonic curing .....	17
Figure 2.14: The electrical conductivity measurement (a) Keithley 2400 current and voltage sources devices (b) Typical Van-der-Pauw sample connection. ....	18
Figure 2.15: Photograph of the Sensofar PLu Neox .....	18
Figure 3.1: The proposed antenna (a) Flat. (b–d) Bent in different directions .....	19
Figure 3.2: Flexible monopole antenna (a) Geometry (b) Fabricated based on a Kapton Polyimide substrate .....	20
Figure 3.3: A photograph of monopole fractal antennas on a Kapton HN film (a) Hilbert (b) Sierpiński arrowhead .....	21
Figure 3.4: The proposed antenna on transparent and flexible substrate.....	21
Figure 3.5: "U-slot" multi-band-monopole antenna (a) radiated side (b) ground side .....	22
Figure 3.6: The fabricated dipole antenna with CPW-feeding .....	23
Figure 3.7: Fabricated LPDA with infinite balun feed ( $130 \times 60 \text{ mm}^2$ ).....	23
Figure 3.8: Manufactured prototype antenna (a) Monopole antenna, and (b) AMC place under the monopole antenna .....	24

Figure 3.9: Photograph of RF energy harvester system.....	25
Figure 3.10: Picture of a matching network (a) a line-stub (b) line stub with soldered components .....	25
Figure 3.11: Printed coplanar waveguide lines (a) the layout (b) picture of printed CPW lines on glass substrate.....	26
Figure 3.12: Microphotographs of silver printed band-pass filter .....	26
Figure 3.13: Photograph of inkjet printing wideband - 3dB branch line coupler .....	27
Figure 3.14: The picture of RFID-tag circuit based on paper substrate.....	27
Figure 4.1: The CPW monopole antenna showing the dimensions calculated in Table 4.1	29
Figure 4.2: (a) Line morphologies for different DSs after photonic sintering with values 45 $\mu$ m, 40 $\mu$ m, 30 $\mu$ m and 25 $\mu$ m, with the DS decreasing from left to right. (b) Scanning electron microscopy of SNP on PET substrate. (c) Micrograph of the printed CPW monopole antenna on PET using SNP taken by the Fludicial camera.....	31
Figure 4.3: The thickness profiles for the printed antenna for DS 30 $\mu$ m (a) thickness of SNP on PET is 350 nm. (b) thickness of SNP on paper is 450 nm .....	33
Figure 4.4: (a) The sheet resistance and the film thickness. (b) the conductivity of SNP on PET and on paper substrates versus drop spacings 30, 35 and 40 $\mu$ m. ....	35
Figure 4.5: Variations of the relative permittivity and the conductivity versus frequency for silver in the GHz and THz ranges.....	36
Figure 4.6: The measured compared to the simulated reflection coefficient $ S_{11} $ (with and without launcher) of SNP on PET substrate at different drop spacing 30 $\mu$ m, 35 $\mu$ m and 40 $\mu$ m. The inset shows the end launcher .....	37
Figure 4.7: The measured compared to the simulated reflection coefficient $ S_{11} $ (with and without launcher) of SNP on paper substrate at different drop spacing 30 $\mu$ m, 35 $\mu$ m and 40 $\mu$ m. The inset shows the end launcher.....	38
Figure 4.8: (a) Picture of printed antenna on PET. (b) picture of the antenna printed on paper.....	40
Figure 5.1: (a) Printed lines morphologies after photonic curing with the DS decreasing from left (35 $\mu$ m) to right (15 $\mu$ m)(b) SEM picture of a printed line on PET substrate at DS 20 $\mu$ m. (c) The formation of agglomeration and bulges in printed lines at drop spacing 15 $\mu$ m after photo sintering for CuONP ink on PET and (d) on Paper.....	43
Figure 5.2: Micrograph of the fabricated CPW monopole antenna showing the dimensions calculated in Table 5.2. ....	44

Figure 5.3: Drop spacing behavior for Copper nanoparticles on PET and Paper substrates against (a) sheet resistance, (b) thickness, (c) line width and (d) conductivity .....	46
Figure 5.4: Variations of the relative permittivity and the conductivity versus frequency for copper in the GHz and THz ranges.....	48
Figure 5.5: Simulated reflection coefficient $ S_{11} $ of CuNP on (a) PET substrate and (b) on paper substrate at different drop spacing 20 $\mu\text{m}$ , 25 $\mu\text{m}$ and 30 $\mu\text{m}$ . ....	49
Figure 5.6: (a) Picture of the antenna printed on PET. (b) Picture of the antenna printed on paper.....	49
Figure 5.7: The measured in comparison with simulated reflection coefficient $ S_{11} $ of CuNP at drop spacing 20 $\mu\text{m}$ . (a) PET substrate (b) paper substrate. The inset shows the end launcher.....	51

## **List of Tables**

Table 2.1 Technology comparison [112, 113] .....	14
Table 2.2 Comparison between paper and PET film properties [124] .....	16
Table 4.1 Geometrical parameters in millimeters for the PET substrate .....	30
Table 4.2 Geometrical parameters in millimeters for the Epson paper substrate .....	30
Table 4.3 Printing and curing conditions used in the fabrication processes .....	32
Table 4.4 Antenna parameters at different DSs for SNP on PET .....	38
Table 4.5 Antenna parameters at different DSs for SNP on paper .....	38
Table 4.6 Simulated and measured radiation pattern of the SNP-CPW monopole antenna at 20 GHz for PET and paper dielectric substrates .....	39
Table 5.1 Printer conditions for PET and Paper substrates .....	42
Table 5.2 Optimized antenna dimensions for PET and paper substrates .....	45
Table 5.3 Antenna parameters at different DSs for CuNP on PET and paper substrates ....	51
Table 5.4 Simulated and measured radiation pattern of the CuNP-CPW monopole antenna at 20 GHz for PET and for paper dielectric substrates .....	52

# List of Abbreviations

IBM	International Business Machines
RF	Radio Frequency
CNT	Carbon Nanotubes
CPW-MA	Coplanar Waveguide Monopole Antenna
CST	Computer System Technology
MWS	Microwave Studios
CVD	Chemical Vapor Deposition
PVD	Physical Vapor Deposition
SEM	Scanning Electron Microscope
TEM	Transmission Electron Microscope
AFM	Atomic Force Microscope
AC	Alternative Current
DC	Direct Current
FIT	Finite Integration Technique
PE	Printed Electronic
RFID	Radio Frequency Identification
UHF	Ultra High Frequency
OLED	Organic Light-Emitting Diode
PCB	Printed Circuit Board
MOD	Metallic Organic Decomposition
DoD	Drop-on-Demand
MEMS	Micro-electromechanical systems
DMP	Dimatix Materials Printed
PET	Polyethylene Terephthalate
SNP	Silver Nanoparticle
VSWR	Voltage Standing Wave Ratio
LPDA	Log Periodic Dipole Array
SLL	Side Lobe Level
AMC	Artificial Magnetic Conductor
BLC	Branch Line Coupler
WBAN	Wireless Body Area Network
HFSS	High Frequency Structure Simulator
IPL	Intense Pulsed Light
XRD	X-ray Diffraction
TL	Transmission Line
BW	Bandwidth
IJPT	Inkjet Printing Technology
DS	Drop spacing
CuONP	Copper Oxide Nanoparticle
VNA	Vector Network Analyzer
DAAD	Deutscher Akademischer Austausch Dienst