FLEXIBLE MATERIALS FOR ULTRA WIDEBAND ANTENNA DESIGN

HUSAMELDIN ABDELRAHMAN ELMOBARAK ELOBAID

UNIVERSITI TEKNOLOGI MALAYSIA

FLEXIBLE MATERIALS FOR ULTRA WIDEBAND ANTENNA DESIGN

HUSAMELDIN ABDELRAHMAN ELMOBARAK ELOBAID

A thesis submitted in fulfillment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

.

APRIL 2018

To my beloved wife: Eman Jaffar Ali and my beloved parents.

ACKNOWLEDGEMENT

I wish to appreciate the Almighty God for His protection, provision and guidance all through the period of my PhD. I express my profound gratitude to my supervisor, Professor Ir. Dr. Sharul Kamal Abdul Rahim for his encouragement, guidance, and ceaseless support throughout this research. I would also like to thank my external-supervisors, Professor Dr. Mohamed Himdi for his advice, motivation and sustainable support.

I am also indebted to all the staff of Wireless Communication Center (WCC), Faculty of Electrical Engineering (FKE), Universiti Teknologi Malaysia (UTM), especially Dr. Igbafe Orikumhi, Dr. Mohamed Abedian and Dr. Bashir Muhammad Saad for their advice and support. I would also like to acknowledge all my colleagues at WCC for their useful views and tips. This work is not complete without the help of IETR research lab in Universite de Rennes 1 in France that assisted in all the fabrication and measurement stage of this research specially Prof Mohamed Himdi, Prof Xavier and Mr Christov. I express my profound gratitude to Ministry of High Education in Malaysia and the Ministry of High Education in Sudan for the financial support. May the Almighty God bless you all and reward you for the kindness.

Finally, I would like to sincerely appreciate my wife, Eman Jaffar for constantly giving me the motivation, support and encouragement to continue with my work. Her prayers, love, patience and understanding contributed immensely to the completion of this work.

ABSTRACT

The demand for ultra-wideband (UWB) antennas increases rapidly with the magnified growth of the wireless systems aiming to support wireless and mobile services by simplifying the systems and to reduce the overall device dimensions, and costs. Vast efforts are offered to the development of UWB antennas that aim to improve the seamless integration with various handheld devices such as laptops, mobile phones, and vehicles such as airplanes, cars, and ships. Consequently, the mechanically flexible antennas are the most suitable for such requirements rather than the antennas based on rigid substrate technology. Hence, the antenna should be conformal and able to be conveniently conformed onto the device's body surface or to be fabricated using the same material in which the devices are fabricated. Subsequently, in some scenarios, the flexible antenna should be optically transparent to overcome the visual impact of the massive use of the antenna in indoor and public areas. Low-cost antenna fabrication technologies are highly expected to take place in future UWB antenna requirements for more economical resource utilization. Generally, UWB systems require the antenna with high efficiency, however, maintaining a high efficiency while achieving extremely wide bandwidth in UWB system is a challenging task. Therefore, conduction and dielectric losses should be minimized in UWB antenna by using highly conductive and low dielectric loss materials. Metals are commonly used as antenna radiating elements because of their high conductivity. However, the poor mechanical flexibility of the metals limit their usage for flexible and conformal applications. The question arises if non-metallic flexible conductive materials having conductivity close to metals can be integrated into the flexible dielectric materials to replace metals. This thesis proposes fabrication techniques to integrate flexible conductive materials into flexible dielectric materials to fabricate transparent UWB antenna and Polymer Matrix Composite (PMC) antenna with improved performance for conformal applications. Moreover, the research evaluates a new low-cost instant printing technique to print UWB flexible antenna with good performance. A technique is proposed to integrate a transparent conductive fabric tissue into a transparent PDMS to fabricate a flexible and transparent UWB antenna with improved performance. The fabricated antenna exhibited an efficiency over 75% and a maximum gain of 4.5 dBi. Moreover, an integration process is proposed to fabricate a flexible PMC composite UWB antenna by integrating the conductive fabric tissue into E-glass fiber mate using Vacuum Infusion Process (VIP). The technology is assessed by fabricating UWB antenna for conformal applications and the results showed high efficiency over 80% for the UWB antenna. Furthermore, a UWB antenna is printed instantly onto a Polyethylene Terephthalate (PET) substrate based on chemical sintering silver inkjet technology using ordinary inkjet printer and the measured results present over 80% of efficiency for antenna.

ABSTRAK

Permintaan terhadap antena ultra jalur lebar (UWB) meningkat dengan pesat seiring pertumbuhan besar sistem tanpa wayar bertujuan untuk menyokong perkhidmatan tanpa wayar dan mudah alih dengan meringkaskan sistem dan mengurangkan dimensi dan kos keseluruhan peranti. Usaha meluas diberikan untuk pembangunan antena UWB yang bertujuan untuk menambah baik persepaduan selanjar dengan pelbagai peranti bimbit seperti komputer riba, telefon mudah alih, dan kenderaan seperti kapal terbang, kereta, dan kapal. Oleh itu, antena yang mudah lentur secara mekanikal adalah paling sesuai untuk keperluan tersebut berbanding antena berasaskan teknologi substrat tegar. Maka, antena harus bersifat menyebentuk dan dapat disesuaikan dengan mudah ke atas permukaan badan peranti atau dibuat dengan menggunakan bahan yang sama seperti peranti tersebut. Selanjutnya, dalam beberapa senario, antena yang fleksibel perlu lutsinar secara optikalnya untuk mengatasi kesan visual penggunaan antena secara besar-besaran di kawasan tertutup dan awam. Teknologi fabrikasi antena berkos rendah dijangka akan memenuhi keperluan antena UWB masa depan untuk penggunaan sumber yang lebih ekonomi. Umumnya, sistem UWB memerlukan antena dengan kecekapan tinggi, namun, mengekalkan kecekapan yang tinggi ketika mencapai lebar jalur yang sangat luas dalam sistem UWB adalah tugas mencabar. Oleh itu, pengaliran dan kehilangan dielektrik harus diminimakan dalam antena UWB dengan menggunakan bahan yang sangat konduktif dan bahan yang kehilangan dielektriknya rendah. Logam biasanya digunakan sebagai elemen pemancaran antena kerana pengalirannya yang tinggi. Walau bagaimanapun, kelenturan mekanikal logam yang lemah menghadkan penggunaannya untuk aplikasi mudah lentur dan menyebentuk. Persoalan timbul jika bahan konduktif mudah lentur bukan-logam yang mempunyai pengaliran yang hampir sama dengan logam dapat dipersepadukan ke dalam bahan dielektrik mudah lentur untuk menggantikan logam. Tesis ini mencadangkan teknik fabrikasi untuk mensepadukan bahan konduktif yang mudah lentur ke dalam bahan dielektrik yang mudah lentur untuk memfabrikasikan antena UWB lutsinar dan antena Komposit Matriks Polimer (PMC) dengan prestasi yang dipertingkatkan untuk aplikasi menyebentuk. Selain itu, kajian ini menilai teknik percetakan segera berkos rendah baharu yang digunakan untuk mencetak antena mudah lentur UWB dengan prestasi yang baik. Teknik ini dicadangkan untuk mensepadukan tisu fabrik konduktif yang lutsinar ke dalam PDMS lutsinar untuk memfabrikasi antena UWB yang mudah lentur dan lutsinar dengan prestasi yang lebih baik. Antena yang difabrikasi menunjukkan kecekapan melebihi 75% dan gandaan maksimum 4.5 dBi. Selain itu, proses persepaduan dicadangkan untuk memfabrikasi antena UWB komposit PMC yang mudah lentur dengan mensepadukan tisu fabrik konduktif ke dalam pasangan gentian E-kaca menggunakan Proses Infusi Vakum (VIP). Teknologi ini dinilai dengan memfabrikasi antena UWB untuk aplikasi menyebentuk dan keputusannya menunjukkan kecekapan tinggi melebihi 80% untuk antena UWB. Tambahan lagi, antena UWB dicetak segera ke atas bahan Polietilena Tereftalat (PET) berdasarkan teknologi inkjet perak pensinteran kimia menggunakan pencetak inkjet biasa dan hasil yang diukur menunjukkan kecekapan melebihi 80% untuk antena.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVATIONS

1-D	-	One Dimensional
2-D	-	Two Dimensional
4G	-	Fourth Generation
5G	-	Fifth Generation
AF	-	Array Factor
Ag	-	Silver
AgHT	-	Silver-coated Polymer
AUT	-	Antenna Under Test
AWR	-	Applied Wave Research
BW	-	Bandwidth
CST	-	Computer Simulation Technology
Cu	-	Copper
CPW	-	Coplanar Waveguide
D2D	-	Device To Device
DOA	-	Direction Of Arrival
EBG	-	Electronic Band Gap
FFT	-	Fast Fourier transform
FIR	-	Finite Impulse Response
FR4	-	Frame Resistance 4

HPBW	-	Half Power Beamwidth
IMT	-	International Mobile Telecommunications
ITU	-	International Telecommunication Union
ITO	-	Indium Tin Oxide
LHCP	-	Left Hand Circular polarization
LTCC	-	Low Temperature Co-fired Ceramics
M2M	-	Machine to Machine
MIMO	-	Multiple Input Multiple Output
MMIC	-	Monolithic Microwave Integrated Circuit
MWS	-	Microwave Studio
NLOS	-	Non-Line of Sight
PCB	-	Printed Circuit Board
PIN	-	Positive-Intrinsic-Negative
PET	-	Polyethylene terephthalate
RF	-	Radio Frequency
RHCP	-	Right Hand Circular polarization
RSS	-	Received Signal Strength
SAS	-	Smart Antenna System
SBSA	-	Switched Beam Smart Antenna
SIR	-	Signal to Interference Ratio
SIW	-	Substrate Integrated Waveguide
SLL	-	Side Lobe Level
VNA	-	Vector Network Analyzer

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

It is worthwhile to note that the sparks radiated by Hertz experiments using a wideband loaded dipoles represent the first generated UWB signals. However, due to the lack of resources at that time, the wideband energy could not be retrieved effectively, therefore the discovered communication setup was abandoned. Later, the radar, sensing, and military communications applications were developed by applying impulse radio technologies during the 1960s and 1970s. Nevertheless, the "Ultra Wideband" term found for the first time by the United State U.S department of defense in 1989. During the 1990s, the UWB systems started to receive a wide interest with the improvement in digital signal processing. In 2002, the interset in UWB system greatly increased when the Federal Communications Commission (FCC) (the frequency regulating body of the United States) decided to release the approving report the use of UWB devices to operate a number of unlicensed frequency bands [0-960 MHz], [3.1-10.6 GHz], and [22-29 GHz]. Subsequently, several regulations were defined by various frequency regulatory bodies around the world [1].

Unlike the conventional carrier wave system, UWB possess abundant unique characteristics which enables it to present an eloquent solution to the broadband wireless systems.

Firstly, UWB system is a sort of base-band signal transmission process that has low cost and low complexities which arise from the fact that it does not modulate and demodulate a complex carrier waveform. Therefore, components such as filters, mixers, amplifiers and local oscillators are not required in UWB transmission.

Secondly, the main aim of the UWB is to achieve very high capacity through the utilization of an ultra-wide bandwidth which can reach up to several Gbps in short distance from 1 to 10 m [2]. Therefore UWB plays a very important role in wideband technologies such as Wireless Personal Area Network (WPAN). It provides a reliable wireless connectivity between portable devices, computers, and consumer electronics via a short range. Furthermore, the high data rate feature enables a fast data exchange and storage between several UWB systems.

Thirdly, the UWB concept is very attractive for the spreading systems since it facilitates optimal bandwidth sharing between various applications and systems. With a very high-frequency adaptive feature, the UWB systems are able to employ the various RF spectrum which enables it to prevent interference to other existing systems while using the entire spectrum. Moreover, the UWB systems nature is immune to the multipath and lossy media effect. The transmission of the UWB systems operates at extremely low level power. Therefore, UWB radio technologies operate at short-range to complements the long-range technologies such as cellular wide area communications, Wireless Fidelity (WiFi), and Worldwide Interoperability for Microwave Access (WiMAX).

Finally, UWB systems provide a highly secure and reliable connectivity solutions. This is because the UWB operates with a low power density which makes the signal comparable to noise signal thereby making it difficult to detect or intercept.

With the increasing growth in wireless communication systems and services, factors such as high data rate, device form factor and cost has led to the increasing demand for wideband, multiband and UWB antennas. Many efforts are offered to integrate various types of conventional rigid antennas and flexible antennas into various handheld devices such as laptops, mobile phones, tablets in addition to the radio base stations and vehicles such as airplanes, cars, and ships. However, the mechanically flexible antennas are the most suitable for such requirements rather than the antennas based on rigid substrate technology such as printed circuit boards (PCB). Hence, the antenna should be conformal to the devices body surface or it should be fabricated using the same material with which the device is fabricated from. Furthermore, the antenna should be designed and fabricated based on highly conductive and flexible materials to be integrated with low loss flexible dielectric materials so that the antenna will gain high performance. The performance should not sacrifice under bending conditions when the antenna is bent. Therefore, new fabrication technologies are required to fabricate UWB antennas from the most common materials that consisting most of the things around us such as ploymer matrix composite (PMC) materials [3]. The PMC composite materials made of polymer material such as epoxy resine called matrix and a reinforcement material such as carbon fiber or glass fiber, are known as a future material that will be the rough material to fabricate different devices and things such as (electronic and electrical devices, house's structure, furniture, vehicles, medical tools and devices, trans, marine boats and ships, aircrafts and many other applications [4, 5].

Moreover, with the increase of wireless communication systems in indoor living spaces and public places, flexible optically transparent antennas are an attractive solution to reduce the visual impact of these systems. For example, the transparent antennas could be used for an indoor security system or in future transparent communication devices such as femtocell [6]. Consequently, the transparent antenna should be able to be conformed to different surfaces and shapes by fabricating the transparent antenna from flexible transparent materials.

The increasing demand for seamless integration of UWB systems with wearable microelectronis to provide low-cost high performance wearable systems. As such, new fabrication techniques should be developed to fabricate flexible UWB antennas using low-cost materials and low-cost fabrication process. In recent years, inkjet printing technologies have been investigated and evaluated to print antennas into flexible printable substrates and films. In addition, low-cost and the simplicity of the fabrication process is a key factor for the technology by instantly printing an antenna that is able to operate efficiently seconds after printing.

1.2 Problem Statement

Due to high data rate, low power and short distance in indoor environment, UWB systems are increasingly being considered for various wireless wearable applications such as flexible microelectronics, wearable devices, and portable electronic gadgets [7, 8]. However, maintaining high radiation efficiency is mandatory to ensure the achievement of the required extremely low transmitted spectral power density for UWB applications and the excessive UWB antenna losses could significantly compromise the whole system functionality.

The demand for wireless wearable applications is increased rapidly in the recent years leading to the employment of a huge amount of antennas in the indoor and public areas. This has increase the demand for flexible antennas that is able to fit into devices of various shapes and sizes, as well as being environmentally friendly to overcome the negative visual impact. Flexible UWB transparent antennas are expected to fulfill these requirements. The flexible UWB antennas have been widely used in various applications, such as vehicle communication and navigation, integration with satellite solar cell panels and with glass for security concerns [9, 10]. However, the fabrication complexity, lossy nature and low efficiency of transparent conductive materials limit the amount of research conducted on such antenna for

UWB applications. Cost reduction and seamless integration is required for the integration of the flexible UWB antennas with handheld devices such as laptops, mobile phones, tablets, radio base stations and various vehicles. Therefore, flexible UWB antennas should be fabricated from or integrated with the materials that most of these devices are fabricated from. Polymer matrix composite (PMC) materials are expected to be the future materials, which will be used in a massive amount of applications [11]. Conductive materials such as carbon fiber composites (CFC) and carbon fiber fabrics have been used as radiating elements in PMC composite antennas. However, its low conductivity is negatively impacting the efficiency, gain and the overall antenna radiation performance [12]. Inkjet printing technology is another factor to be considered to achieve the low cost and seamless integration of antennas with microelectronic systems based on low cost substrates such as polymeric materials and papers. Several technologies have been proposed recently by using silver nanoparticles ink based onto a different flexible substrate such as Kapton polyimide [13], papers [14] and polyethylene terephthalate (PET) [15]. Most of the reported inkjet printing methods are based on thermal sintering, which requires long time process for ink thermal curing to achieve the highest conductivity. Moreover, the main bottleneck in inkjet-printed features on flexible polymeric substrates is the low softening point of the substrate or the amount of temperature that when reached the substrate material will melt or burned, which limits the processing temperature. The softening point of commonly used polymeric substrates, like PET or polycarbonate (PC), is lower than 150° C. Typically, colloidal suspensions of conductive materials need a sintering temperature higher than 200° C, which is hence not compatible with most polymeric substrates [16].

The use of highly conductive flexible materials as radiating elements can improve the low radiation efficiency due to high conduction losses in the flexible UWB transparent and PMC composite antennas. Consequently, a method is required to produce a flexible transparent antenna with improved radiation efficiency by integrating highly conductive flexible transparent material with low loss transparent and flexible dielectric material. Polymer material such as PDMS possess high optical transparency, mechanical flexibility, high ability for integration with other materials and low tangent loss around (Ɛr = 2.85 at 10 GHz), can be used as a transparent substrate. Similarly, a fabrication method should be developed to integrate a high conductive material which is suitable for resin lamination to be embedded with the reinforcement fibers such as carbon fiber or glass fibers to produce a fully PMC composite antenna. Conductive fabrics can be good choice because it has high conductivity and the mesh style of the fabric will help in absorbing the resin and hence allow full lamination and integration with the PMC composites. The free sintering inkjet printing technologies in which the conductive ink can be cured in room temperature can provide a low cost, low processing time and seamless integration for flexible UWB antennas with microelectronic and wearable devices.

In summary, the currently used transparent conductive films have poor conductivity which significantly affects the antenna radiation performance. Therefore, integrating highly conductive transparent and flexible material with low loss transparent and flexible dielectric material can produce low loss transparent UWB antenna. In addition, the use of highly conductive materials to integrate with PMC composite materials will produce a fully PMC composite antenna with high radiation performance. Moreover, new inkjet printing technologies having superior features such as low cost, sintering free and high conductivity can produce a low cost, low processing time and seamless integration method to integrate the UWB antennas into various microelectronics and wearable devices.

1.3 Research Objectives

This research has the following objectives:

i. To develop a method to improve the radiation performance of the flexible transparent antenna by using highly conductive flexible transparent material and to verify the method by fabricating a flexible transparent UWB antenna for conformal antenna applications.

ii. To develop a method to improve the radiation performance of the flexible PMC composite antenna by using highly conductive flexible material and to verify the method by fabricating a flexible PMC composite UWB antenna for conformal antenna applications.

iii. To investigate the use of a chemically sintered low cost silver-nano ink for inkjet printing technology, to instantly print flexible UWB antenna.

1.4 Scope of Work

This study is limited to develop a method to integrate a highly conductive flexible material onto a flexible dielectric materials to produce a flexible antenna with significantly enhanced radiation performance in terms of efficiency and gain for conformal applications for UWB systems and future wireless networks. The study focused on flexible transparent antenna technology, flexible polymer matrix composite (PMC) antenna technology based on composite laminate material made of E-glass fiber mat and epoxy resin. Moreover, the study investigated the use a low cost chemicaly sintered silver-nano inkjet printing technology for printed flexible UWB antenna. The study focused on the conformal antenna case where the antenna is bent to a certain curved surface.

CST microwave studio© software is used in designing the flexible antenna prototypes, testing, and optimization. Moreover, the bending test will be conducted by bending the antennas on a loss less surface such as flexible foam having dielectric constant and tangent loss closed to air. The study also includes measuring the radiation performance of the antenna such as (S_{11}, radiation pattern, gain, and efficiency).

1.5 Research Contributions

The research, major contributions are listed below:

a. A Transparent and Flexible Fabric -Polymer Tissue Fabrication Technique for UWB Antenna

In this contribution, the study has proposed a method to integrate a flexible transparent and highly conductive fabric tissue onto a PDMS substrate with a thickness of 2 mm to produce a transparent conductive film with very low sheet resistivity Rs = 0.089 ohm/sq compared to the conventional transparent conductive films such as indium tin oxide ITO and silver-coated polymer (AgHt) having sheet resistivity of (2-15) ohm/sq. Due to the high sheet resistivity of the conventional TCF, transparent antennas made of this kind of TCF suffer from high loss and thus exhibit low efficiency. Therefore, the low sheet resistivity of the produced TCF using the proposed method will help in reducing the losses and hence improve the antenna efficiency. Then the method proposed a laser etching process to fabricate a flexible transparent UWB antenna precisely. The fabricated UWB antenna exhibits an average measured radiation efficiency of 75% throughout the operating band, and shows a maximum gain of 4.5 dBi at 18 GHz and a stable radiation pattern. It performs well under bending conditions, as observed from the measured results.

b. A Flexible Fabric/ E-glass Fiber PMC Composite Fabrication Technique for UWB Antenna

A full flexible PMC composite antenna with high radiation performance is fabricated using highly conductive fabric as a radiating element compared to a reference antenna made of a metal conductor. The contribution of this technique is to improve the radiation efficiency of the composite antenna by integrating the composite dielectric material with a highly conductive material suitable for integration with composites. Therefore, a thin sheet of a highly conductive fabric with high conductivity of 2×10^5 S/m is embedded by infusion process in a thin composite laminate made of E-glass fiber mat and epoxy resin to produce a flexible conductive PMC composite film to be used for the fabrication of a UWB antenna with high radiation performance. The composite antenna made of the conventional conductive composite materials such as carbon fiber composite (CFC) and carbon fiber fabrics suffer from high losses and poor radiation efficiency due to the low conductivity of these materials which is about (3.5×10^2 S/m – 3×10^4 S/m). In addition, the fabric mesh style of the conductive fabric makes it very suitable to be laminated with resin and thus seamless integration with composite material. Moreover, the fabrication technique proposes a laser etching method for precise antenna fabrication where the conductive fabric is embedded inside the resin; therefore, the laser will etch the unnecessary parts of the fabric without affecting the dielectric substrate. The fabrication technique is validated by fabricating a UWB antenna. The fabricated antenna exhibited a measured radiation efficiency reaches over 80% averaged value throughout the operating frequency band with a maximum gain of 3.1 dBi at 5 GHz and stable radiation patterns. The composite antenna performs well under bending conditions as demonstrated by the measurements.

c. A Low Cost Instant Inkjet-Printed Flexible UWB Antenna

This contribution investigated low-cost silver–nano inkjet printing technology for seamless integration of the UWB antennas with printable electronics and systems. The investigated printing technology possesses superior properties such as low cost, room temperature fast sintering and low processing time compared to the conventional silver–nano printing technology based on thermal sintering. A UWB antenna is printed onto a PET film and the printed traces are sintered instantly where the highest conductivity value achieved within few seconds without any further sintering process and without affecting the polymer substrate. The antenna elements are printed precisely using an ordinary inkjet printer. The antenna operates effectively in the 3.3 GHz - 12 GHz band. Its radiation efficiency reaches over 80% average value throughout the operating frequency band with stable radiation patterns. It exhibits highly flexible mechanical properties enabling it to be bent without sacrificing its performance.

1.6 Thesis Outline

This thesis is outlined in seven chapters. The first chapter presents the overall view of the project, which includes the research background, problem statement, the research objectives, the contributions to knowledge, the research scope, and the thesis organization.

The second chapter reviews the literature. The chapter discusses structural aspects of the flexible antenna and the electrical characteristics of flexible materials. Also, the requirements and challenges of transparent, composite and inkjet printed antenna applications are presented.

The methodology used to realize the proposed technologies and the antenna design are discussed in Chapter 3 initiated with the detail discussion of the research framework. The step by step fabrication technology which proposed in this research to fabricate flexible transparent antenna, flexible PMC composite antenna and the inkjet printed antenna is presented. In addition, the fabrication and measurement procedures and tools used are demonstrated. The design specifications and parameters used to achieve the desired results are demonstrated.

Chapter 4 discuss the validation of the flexible transparent antenna technique presented in chapter 3 through the design and fabrication of a UWB antenna. The antenna radiation performance has been evaluated via analysing the measurement and simulated results of the return loss, gain, efficiency and radiation patter. At the end of the chapter the achieved antenna performance results has been compared to the previous reported flexible transparent antenna radiation performance.

Chapter 5 illustrate the validation of the flexible PMC composite antenna technique presented in chapter 3 by designing and fabricating a UWB antenna. To evaluate the antenna radiation performance, the measurement and simulated results of the return loss, gain, efficiency and radiation patter has been compared and analysed. At the end of the chapter the achieved antenna performance results has been compared to the previous reported flexible composite antenna radiation performance.

Chapter 6 demonstrates the evaluation of a sintering free and instant inkjet printing technology for printed flexible UWB antenna applications. The technology assessment has been presented throughout the chapter by printing UWB antenna and discussing the performance results.

Finally, the conclusion and the recommendations for further work are presented Chapter 7. The achievements of the research and future works recommendations are depicted. A list of the references and some appendices are documented at the end.

REFERENCE

[1] Y. Duroc and A. I. Najam, *UWB antennas: design and modeling*: INTECH Open Access Publisher, 2010.

[2] I. Oppermann, M. Hämäläinen, and J. Iinatti, *UWB: theory and applications*: John Wiley & Sons, 2005.

[3] R. Cicchetti, E. Miozzi, and O. Testa, "Wideband and UWB antennas for wireless applications: a comprehensive review," *International Journal of Antennas and Propagation,* 2017.

[4] R. F. Gibson, "A review of recent research on mechanics of multifunctional composite materials and structures," *Composite structures,* vol. 92, pp. 2793-2810, 2010.

[5] G. Gupta, A. Kumar, R. Tyagi, and S. Kumar, "Application and Future of Composite Materials: A Review," *Int. J. Innov. Res. Sci. Technol,* vol. 5, pp. 6907-6911, 2016.

[6] J. R. Saberin and C. Furse, "Challenges with optically transparent patch antennas," *IEEE Antennas and Propagation Magazine,* vol. 54, pp. 10-16, 2012.

[7] Y. Hao, A. Alomainy, P. Hall, Y. Nechayev, C. Parini, and C. Constantinou, "Antennas and propagation for body centric wireless communications," in *Wireless Communications and Applied Computational Electromagnetics, 2005. IEEE/ACES International Conference on*, 2005, pp. 586-589.

[8] A. Fort, C. Desset, P. De Doncker, P. Wambacq, and L. Van Biesen, "An ultra-wideband body area propagation channel model-from statistics to implementation," *IEEE Transactions on Microwave Theory and Techniques,* vol. 54, pp. 1820-1826, 2006.

[9] C.-T. Lee, C.-M. Lee, and C.-H. Luo, "The transparent monopole antenna for WCDMA and WLAN," in *2006 IEEE Annual Wireless and Microwave Technology Conference,* 2006, pp. 1-3.

[10] R. N. Simons and R. Q. Lee, "Feasibility study of optically transparent microstrip patch antenna," 1997.

[11] M. Gururaja and A. H. Rao, "A review on recent applications and future prospectus of hybrid composites," *Int J Soft Comput Eng,* vol. 1, pp. 352-5, 2012.

[12] L. Manac'h, X. Castel, and M. Himdi, "Performance of a lozenge monopole antenna made of pure composite laminate," *Progress In Electromagnetics Research Letters,* vol. 35, pp. 115-123, 2012.

[13] S. Ahmed, F. A. Tahir, A. Shamim, and H. M. Cheema, "A Compact Kapton-Based Inkjet-Printed Multiband Antenna for Flexible Wireless Devices," *IEEE Antennas and Wireless Propagation Letters,* vol. 14, pp. 1802-1805, 2015.

[14] A. Rida, L. Yang, R. Vyas, and M. M. Tentzeris, "Conductive inkjet-printed antennas on flexible low-cost paper-based substrates for RFID and WSN applications," *IEEE Antennas and Propagation Magazine,* vol. 51, pp. 13-23, 2009.

[15] G. A. Casula, G. Montisci, and G. Mazzarella, "A wideband PET inkjet-printed antenna for UHF RFID," *IEEE Antennas and Wireless Propagation Letters,* vol. 12, pp. 1400-1403, 2013.

[16] T. H. Van Osch, J. Perelaer, A. W. de Laat, and U. S. Schubert, "Inkjet printing of narrow conductive tracks on untreated polymeric substrates," *Advanced Materials,* vol. 20, pp. 343-345, 2008.

[17] G. DeJean, R. Bairavasubramanian, D. Thompson, G. Ponchak, M. Tentzeris, and J. Papapolymerou, "Liquid crystal polymer (LCP): a new organic material for the development of multilayer dual-frequency/dual-polarization flexible antenna arrays," *IEEE Antennas and Wireless Propagation Letters,* vol. 4, pp. 22-26, 2005.

[18] L. Marnat and A. Shamim, "Liquid crystal polymer (LCP) based antenna for flexible system on package (SoP) applications," in *Antenna Technology and Applied Electromagnetics (ANTEM), 2012 15th International Symposium on*, 2012, pp. 1-4.

[19] P. Cabrol and P. Pietraski, "60 GHz patch antenna array on low cost liquid-crystal polymer (LCP) substrate," in *Systems, Applications and Technology Conference (LISAT), 2014 IEEE Long Island*, 2014, pp. 1-6.

[20] H. Liu, S. Zhu, P. Wen, X. Xiao, W. Che, and X. Guan, "Flexible CPW-fed fishtail-shaped antenna for dual-band applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 770-773, 2014.

[21] A. Bondarik and D. Sjöberg, "60 GHz microstrip antenna array on PTFE substrate," in *Antennas and Propagation (EUCAP), 2012 6th European Conference on*, 2012, pp. 1016-1018.

[22] K. Hettak, T. Ross, R. James, A. Momciu, and J. Wight, "Flexible polyethylene terephthalate-based inkjet printed CPW-fed monopole antenna for 60 GHz ISM applications," in *Microwave Integrated Circuits Conference (EuMIC), 2013 European*, 2013, pp. 476-479.

[23] T. Peter, T. A. Rahman, S. Cheung, R. Nilavalan, H. F. Abutarboush, and A. Vilches, "A novel transparent UWB antenna for photovoltaic solar panel integration and RF energy harvesting," *IEEE Transactions on Antennas and Propagation,* vol. 62, pp. 1844-1853, 2014.

[24] M. Rani, S. K. A. Rahim, M. R. Kamarudin, T. Peter, S. Cheung, and B. Saad, "Electromagnetic behaviors of thin film CPW-fed CSRR loaded on UWB transparent antenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 13, pp. 1239-1242, 2014.

[25] T. Peter, "Optically transparent UWB antenna for wireless application & energy harvesting," Brunel University School of Engineering and Design PhD Theses, 2012.

[26] S. Hakimi, S. K. A. Rahim, M. Abedian, S. Noghabaei, and M. Khalily, "CPW-fed transparent antenna for extended ultrawideband applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 13, pp. 1251-1254, 2014.

[27] M. A. Eddings, M. A. Johnson, and B. K. Gale, "Determining the optimal PDMS–PDMS bonding technique for microfluidic devices," *Journal of Micromechanics and Microengineering,* vol. 18, p. 067001, 2008.

[28] C.-P. Lin, C.-H. Chang, Y. Cheng, and C. F. Jou, "Development of a flexible SU-8/PDMS-based antenna," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 1108-1111, 2011.

[29] J. Trajkovikj, J.-F. Zürcher, and A. K. Skrivervik, "PDMS, a robust casing for flexible W-BAN antennas [EurAAP corner]," *IEEE Antennas and Propagation Magazine,* vol. 55, pp. 287-297, 2013.

[30] N. Tiercelin, P. Coquet, R. Sauleau, V. Senez, and H. Fujita, "Polydimethylsiloxane membranes for millimeter-wave planar ultra flexible antennas," *Journal of Micromechanics and Microengineering,* vol. 16, p. 2389, 2006.

[31] M. A. Osman, M. Rahim, N. Samsuri, M. Elbasheer, and M. Ali, "Textile UWB antenna bending and wet performances," *International Journal of Antennas and Propagation,* vol. 2012, 2012.

[32] M. E. Jalil, M. K. A. Rahim, M. A. Abdullah, and O. Ayop, "Compact CPW-fed ultra-wideband (UWB) antenna using denim textile material," in *Antennas and Propagation (ISAP), 2012 International Symposium on*, 2012, pp. 30-33.

[33] S. Cheng, Z. Wu, P. Hallbjorner, K. Hjort, and A. Rydberg, "Foldable and stretchable liquid metal planar inverted cone antenna," *IEEE Transactions on antennas and propagation,* vol. 57, pp. 3765-3771, 2009.

[34] Y. Zhou, Y. Bayram, F. Du, L. Dai, and J. L. Volakis, "Polymer-carbon nanotube sheets for conformal load bearing antennas," *IEEE Transactions on Antennas and Propagation,* vol. 58, pp. 2169-2175, 2010.

[35] (2016). *Conductive Textile* Available: www.lessemf.com/fabric_guide.html

[36] *conductive textile* Available: https://www.sparkfun.com/

[37] J. Liang, C. C. Chiau, X. Chen, and C. G. Parini, "Study of a printed circular disc monopole antenna for UWB systems," *IEEE Transactions on antennas and propagation,* vol. 53, pp. 3500-3504, 2005.

[38] L. Josefsson and P. Persson, "Scattering from Conformal Arrays," *Conformal Array Antenna Theory and Design,* pp. 421-461.

[39] P. Salonen, J. Kim, and Y. Rahmat-Samii, "Dual-band E-shaped patch wearable textile antenna," in *Antennas and propagation society international symposium, 2005 IEEE,* 2005, pp. 466-469.

[40] F. Colombel, X. Castel, M. Himdi, G. Legeay, S. Vigneron, and E. MOTTA CRUZ, "Ultrathin metal layer, ITO film and ITO/Cu/ITO multilayer towards transparent antenna," *IET science, measurement & technology,* vol. 3, pp. 229-234, 2009.

[41] T. W. Turpin and R. Baktur, "Meshed patch antennas integrated on solar cells," *IEEE Antennas and Wireless Propagation Letters,* vol. 8, pp. 693-696, 2009.

[42] G. Clasen and R. Langley, "Meshed patch antennas," *IEEE Transactions on Antennas and Propagation,* vol. 52, pp. 1412-1416, 2004.

[43] N. M. Ali, N. Misran, M. Mansor, and M. Jamlos, "Transparent solar antenna of 28 GHz using transparent conductive oxides (TCO) thin film," in *Journal of Physics: Conference Series,* 2017, p. 012036.

[44] Z. Meng, H. Peng, C. Wu, J. Li, S. Xiong, C. F. Qiu, *et al.*, "Room temperature deposition of thin-film indium-tin oxide on micro-fabricated color filters and its application to flat-panel displays," *Guangdianzi Jiguang/Journal of Optoelectronics Laser,* vol. 16, p. 140, 2005.

[45] J. Hautcoeur, L. Talbi, K. Hettak, and M. Nedil, "60 GHz optically transparent microstrip antenna made of meshed AuGL material," *IET Microwaves, Antennas & Propagation,* vol. 8, pp. 1091-1096, 2014.

[46] J. Van De Groep, P. Spinelli, and A. Polman, "Transparent conducting silver nanowire networks," *Nano letters,* vol. 12, pp. 3138-3144, 2012.

[47] N. Durán, P. D. Marcato, O. L. Alves, G. I. De Souza, and E. Esposito, "Mechanistic aspects of biosynthesis of silver nanoparticles by several Fusarium oxysporum strains," *Journal of nanobiotechnology,* vol. 3, p. 8, 2005.

[48] Y. Zhu, S. Murali, W. Cai, X. Li, J. W. Suk, J. R. Potts, *et al.*, "Graphene and graphene oxide: synthesis, properties, and applications," *Advanced materials,* vol. 22, pp. 3906-3924, 2010.

[49] M. Neek-Amal and F. Peeters, "Lattice thermal properties of graphane: thermal contraction, roughness, and heat capacity," *Physical Review B,* vol. 83, p. 235437, 2011.

[50] C. Zhou, S. Chen, J. Lou, J. Wang, Q. Yang, C. Liu, *et al.*, "Graphene’s cousin: the present and future of graphane," *Nanoscale research letters,* vol. 9, p. 26, 2014.

[51] J. C. Garcia, D. B. de Lima, L. V. Assali, and J. F. Justo, "Group IV graphene-and graphane-like nanosheets," *The Journal of Physical Chemistry C,* vol. 115, pp. 13242-13246, 2011.

[52] Y.-E. Yang, Y.-R. Yang, and X.-H. Yan, "Universal optical properties of graphane nanoribbons: a first-principles study," *Physica E: Low-Dimensional Systems and Nanostructures,* vol. 44, pp. 1406-1409, 2012.

[53] A. R. Madaria, A. Kumar, F. N. Ishikawa, and C. Zhou, "Uniform, highly conductive, and patterned transparent films of a percolating silver nanowire network on rigid and flexible substrates using a dry transfer technique," *Nano Research,* vol. 3, pp. 564-573, 2010.

[54] Y. Sun, "Silver nanowires–unique templates for functional nanostructures," *Nanoscale,* vol. 2, pp. 1626-1642, 2010.

[55] C.-H. Liu and X. Yu, "Silver nanowire-based transparent, flexible, and conductive thin film," *Nanoscale research letters,* vol. 6, p. 75, 2011.

[56] S. De and J. N. Coleman, "Are there fundamental limitations on the sheet resistance and transmittance of thin graphene films?," *Acs Nano,* vol. 4, pp. 2713-2720, 2010.

[57] H.-Z. Geng, K. K. Kim, K. P. So, Y. S. Lee, Y. Chang, and Y. H. Lee, "Effect of acid treatment on carbon nanotube-based flexible transparent conducting films," *Journal of the American Chemical Society,* vol. 129, pp. 7758-7759, 2007.

[58] R. V. Gorbachev, A. S. Mayorov, A. K. Savchenko, D. W. Horsell, and F. Guinea, "Conductance of pnp graphene structures with “Air-Bridge” top gates," *Nano letters,* vol. 8, pp. 1995-1999, 2008.

[59] A. K. Geim and K. S. Novoselov, "The rise of graphene," *Nature materials,* vol. 6, pp. 183-191, 2007.

[60] W. Choi, I. Lahiri, R. Seelaboyina, and Y. S. Kang, "Synthesis of graphene and its applications: a review," *Critical Reviews in Solid State and Materials Sciences,* vol. 35, pp. 52-71, 2010.

[61] B. Gharekhanlou, S. Tousaki, and S. Khorasani, "Bipolar transistor based on graphane," in *Journal of Physics: Conference Series*, 2010, p. 012061.

[62] Q. Jiwei, L. Yudong, Y. Ming, W. Qiang, C. Zongqiang, P. Jingyang, *et al.*, "Fabrication of nanowire network AAO and its application in SERS," *Nanoscale research letters,* vol. 8, p. 495, 2013.

[63] C. Mias, C. Tsakonas, N. Prountzos, D. Koutsogeorgis, S. Liew, C. Oswald, *et al.*, "Optically transparent microstrip antennas," in *Antennas for Automotives (Ref. No. 2000/002), IEE Colloquium on*, 2000, pp. 8/1-8/6.

[64] N. Guan, H. Furuya, D. Delaune, and K. Ito, "Antennas made of transparent conductive films," *PIERS online,* vol. 4, pp. 116-120, 2008.

[65] A. Katsounaros, Y. Hao, N. Collings, and W. Crossland, "Optically transparent ultra-wideband antenna," *Electronics letters,* vol. 45, pp. 722-723, 2009.

[66] N. J. Kirsch, N. A. Vacirca, E. E. Plowman, T. P. Kurzweg, A. K. Fontecchio, and K. R. Dandekar, "Optically transparent conductive polymer RFID meandering dipole antenna," in *2009 IEEE International Conference on RFID*, 2009.

[67] T. Peter, Y. Sun, T. Yuk, H. AbuTarboush, R. Nilavalan, and S. Cheung, "Miniature transparent UWB antenna with tunable notch for green wireless applications," in *Antenna Technology (iWAT), 2011 International Workshop on*, 2011, pp. 259-262.

[68] T. Peter, R. Nilavalan, H. F. AbuTarboush, and S. Cheung, "A novel technique and soldering method to improve performance of transparent polymer antennas," *IEEE Antennas and Wireless Propagation Letters,* vol. 9, pp. 918-921, 2010.

[69] T. Yasin, R. Baktur, and C. Furse, "A study on the efficiency of transparent patch antennas designed from conductive oxide films," in *Antennas and Propagation (APSURSI), 2011 IEEE International Symposium on*, 2011, pp. 3085-3087.

[70] S. Hong, S. H. Kang, Y. Kim, and C. W. Jung, "Transparent and Flexible Antenna for Wearable Glasses Applications," *IEEE Transactions on Antennas and Propagation,* vol. 64, pp. 2797-2804, 2016.

[71] Y. Kim, C. Lee, S. Hong, C. W. Jung, and Y. Kim, "Design of transparent multilayer film antenna for wireless communication," *Electronics Letters,* vol. 51, pp. 12-14, 2014.

[72] M. R. Haraty, M. Naser-Moghadasi, A. A. Lotfi-Neyestanak, and A. Nikfarjam, "Improving the Efficiency of Transparent Antenna Using Gold Nanolayer Deposition," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, pp. 4-7, 2016.

[73] S. Hong, Y. Kim, and C. W. Jung, "Transparent Microstrip Patch Antennas With Multilayer and Metal-Mesh Films," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, pp. 772-775, 2017.

[74] Q. Li, S. Cheung, D. Wu, and T. Yuk, "Optically Transparent Dual-Band MIMO Antenna Using Micro-Metal Mesh Conductive Film for WLAN System," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, pp. 920-923, 2017.

[75] T. Peter, R. Nilavalan, and S. Cheung, "A Novel Transparent TSA for Laptop and UWB Applications," *PIERS Proceedings, Kuala Lumpur, MALAYSIA,* 2012.

[76] M. Malek, S. Hakimi, S. A. Rahim, and A. Evizal, "Dual-band CPW-fed transparent antenna for active RFID tags," *IEEE Antennas and Wireless Propagation Letters,* vol. 14, pp. 919-922, 2015.

[77] S. Sheikh, M. Shokooh-Saremi, and M.-M. Bagheri-Mohagheghi, "Transparent microstrip patch antenna based on fluorine-doped tin oxide deposited by spray pyrolysis technique," *IET Microwaves, Antennas & Propagation,* vol. 9, pp. 1221-1229, 2015.

[78] (2017). *Guide To Composite Materials.* Available: http://www.netcomposites.com/education.asp?sequence=2

[79] A. D. McNaught and A. D. McNaught, *Compendium of chemical terminology* vol. 1669: Blackwell Science Oxford, 1997.

[80] D. Pathania and D. Singh, "A review on electrical properties of fiber reinforced polymer composites," *International journal of theoretical & applied sciences,* vol. 1, pp. 34-37, 2009.

[81] M. Mrazova, "Advanced composite materials of the future in aerospace industry," *Incas bulletin,* vol. 5, p. 139, 2013.

[82] J. HINRICHSEN, "Airbus A380: Requirements for the selection of materials and manufacturing technologies," *ATB Métallurgie,* vol. 41, pp. 24-30, 2001.

[83] P. Jerome, "Composite materials in the airbus A380-from history to future," 2001.

[84] R. R. d. Assis and I. Bianchi, "Analysis of microstrip antennas on carbon fiber composite material," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications,* vol. 11, pp. 154-161, 2012.

[85] B. Karthikeyan, S. Ramanathan, and V. Ramakrishnan, "Thermo physical property measurement of metal-matrix composites," *Materials & Design,* vol. 31, pp. S82-S86, 2010.

[86] E. Mangino, J. Carruthers, and G. Pitarresi, "The future use of structural composite materials in the automotive industry," *International Journal of vehicle design,* vol. 44, pp. 211-232, 2007.

[87] M. Won, T. Park, and S. H. Son, "Toward Mitigating Phantom Jam Using Vehicle-to-Vehicle Communication," *IEEE Transactions on Intelligent Transportation Systems,* vol. 18, pp. 1313-1324, 2017.

[88] L. Zhang, H. Ma, D. Shi, P. Wang, G. Cai, and X. Liu, "Reliability Oriented Modeling and Analysis of Vehicular Power Line Communication for Vehicle to Grid (V2G) Information Exchange system," *IEEE Access,* 2017.

[89] E. Salernitano and C. Migliaresi, "Composite materials for biomedical applications: a review," *Journal of Applied Biomaterials & Biomechanics,* vol. 1, pp. 3-18, 2003.

[90] M. Drewry and G. Georgiou, "A review of NDT techniques for wind turbines," *Insight-Non-Destructive Testing and Condition Monitoring,* vol. 49, pp. 137-141, 2007.

[91] B. Suddell, "Industrial fibres: recent and current developments," in *Symposium on Natural Fibres,* 2008.

[92] J. L. Wang, "Application of Composite Materials on Sports Equipments," in *Applied Mechanics and Materials,* 2012, pp. 903-906.

[93] F. Froes, "Is the use of advanced materials in sports equipment unethical?," *JOM Journal of the Minerals, Metals and Materials Society,* vol. 49, pp. 15-19, 1997.

[94] M. Lila, F. Kumar, and S. Sharma, "Composites from waste for civil engineering applications," *i-Manager's Journal on Material Science,* vol. 1, p. 1, 2013.

[95] H. Rmili, J. L. Miane, H. Zangar, and T. Olinga, "Design of microstrip-fed proximity-coupled conducting-polymer patch antenna," *Microwave and Optical Technology Letters,* vol. 48, pp. 655-660, 2006.

[96] Y. Bayram, Y. Zhou, J. Volakis, B. Shim, and N. Kotov, "Conductive textiles and polymer-ceramic composites for novel load bearing antennas," in *2008 IEEE Antennas and Propagation Society International Symposium,* 2008, pp. 1-4.

[97] L. Yang, A. Rida, R. Vyas, and M. M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," *IEEE Transactions on Microwave Theory and Techniques,* vol. 55, pp. 2894-2901, 2007.

[98] R. Tellakula, V. Varadan, T. Shami, and G. Mathur, "Carbon fiber and nanotube based composites with polypyrrole fabric as electromagnetic absorbers," *Smart materials and structures,* vol. 13, p. 1040, 2004.

[99] I. M. De Rosa, F. Sarasini, M. S. Sarto, and A. Tamburrano, "EMC impact of advanced carbon fiber/carbon nanotube reinforced composites for next-generation aerospace applications," *IEEE Transactions on Electromagnetic Compatibility,* vol. 50, pp. 556-563, 2008.

[100] C. L. Holloway, M. S. Sarto, and M. Johansson, "Analyzing carbon-fiber composite materials with equivalent-layer models," *IEEE Transactions on Electromagnetic Compatibility,* vol. 47, pp. 833-844, 2005.

[101] W. Bauhofer and J. Z. Kovacs, "A review and analysis of electrical percolation in carbon nanotube polymer composites," *Composites Science and Technology,* vol. 69, pp. 1486-1498, 2009.

[102] R. K. Challa, D. Kajfez, V. Demir, J. R. Gladden, and A. Z. Elsherbeni, "Characterization of multiwalled carbon nanotube (MWCNT) composites in a waveguide of square cross section," *IEEE Microwave and Wireless Components Letters,* vol. 18, pp. 161-163, 2008.

[103] B. Hornbostel, U. Leute, P. Pötschke, J. Kotz, D. Kornfeld, P.-W. Chiu*, et al.*, "Attenuation of electromagnetic waves by carbon nanotube composites," *Physica E: Low-dimensional Systems and Nanostructures,* vol. 40, pp. 2425-2429, 2008.

[104] C. Buccella, "Quasi-stationary analysis of the electric field in anisotropic laminated composites," *IEEE Transactions on Industry Applications,* vol. 35, pp. 1296-1305, 1999.

[105] Y. Huang, N. Li, Y. Ma, F. Du, F. Li, X. He, *et al.*, "The influence of single-walled carbon nanotube structure on the electromagnetic interference shielding efficiency of its epoxy composites," *Carbon,* vol. 45, pp. 1614-1621, 2007.

[106] I. D. Rosca and S. V. Hoa, "Highly conductive multiwall carbon nanotube and epoxy composites produced by three-roll milling," *Carbon,* vol. 47, pp. 1958-1968, 2009.

[107] A. Mehdipour, I. D. Rosca, A. Sebak, C. Trueman, and S. Hoa, "Advanced carbon-fiber composite materials for RFID tag antenna applications," *Appl. Comput. Electromagn. Soc.(ACES) J,* vol. 25, 2010.

[108] A. Galehdar, W. S. Rowe, K. Ghorbani, P. J. Callus, S. John, and C. H. Wang, "The effect of ply orientation on the performance of antennas in or on carbon fiber composites," *Progress In Electromagnetics Research,* vol. 116, pp. 123-136, 2011.

[109] A. Mehdipour, C. Trueman, A. Sebak, and S. Hoa, "Carbon-fiber composite T-match folded bow-tie antenna for RFID applications," in *2009 IEEE Antennas and Propagation Society International Symposium*, 2009, pp. 1-4.

[110] A. Galehdar, P. J. Callus, and K. Ghorbani, "A novel method of conductivity measurements for carbon-fiber monopole antenna," *IEEE Transactions on Antennas and Propagation,* vol. 59, pp. 2120-2126, 2011.

[111] M. S. Sarto, "Hybrid MFIE/FDTD analysis of the shielding effectiveness of a composite enclosure excited by a transient plane wave," *IEEE transactions on magnetics,* vol. 36, pp. 946-950, 2000.

[112] A. Mehdipour, A.-R. Sebak, C. W. Trueman, I. D. Rosca, and S. V. Hoa, "Reinforced continuous carbon-fiber composites using multi-wall carbon nanotubes for wideband antenna applications," *IEEE Transactions on Antennas and Propagation,* vol. 58, pp. 2451-2456, 2010.

[113] A. Mehdipour, I. D. Rosca, A.-R. Sebak, C. W. Trueman, and S. V. Hoa, "Full-composite fractal antenna using carbon nanotubes for multiband

wireless applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 9, pp. 891-894, 2010.

[114] L. Manac'h, X. Castel, and M. Himdi, "Microwave performance of a carbon composite antenna," in *Microwave Conference (EuMC), 2013 European*, 2013, pp. 770-773.

[115] S. S. Bhore, "Formulation and Evaluation of Resistive Inks for Applications in Printed Electronics," 2012.

[116] J. E. Neff, "Investigation of the effects of process parameters on performance of gravure printed ITO on flexible substrates," Citeseer, 2009.

[117] S. S. Joshi, "Evaluation of Silver/Graphite Ink Blends for Use in Printed Electronics," 2011.

[118] A. Karwa, "Printing studies with conductive inks and exploration of new conducting polymer compositions," 2006.

[119] N. D. Sankır, "Flexible electronics: materials and device fabrication," Virginia Polytechnic Institute and State University, 2005.

[120] K. Eiroma, L. Hakola, J. Hast, A. Maaninen, and J. Petäjä, "UV Curing for Printed."

[121] J. R. Greer and R. A. Street, "Thermal cure effects on electrical performance of nanoparticle silver inks," *Acta Materialia,* vol. 55, pp. 6345-6349, 2007.

[122] K. Gilleo, *Polymer thick film: today's emerging technology for a clean environment tomorrow*: Springer Science & Business Media, 1996.

[123] S.-S. Yoon and D.-Y. Khang, "Room-temperature chemical welding and sintering of metallic nanostructures by capillary condensation," *Nano letters,* vol. 16, pp. 3550-3556, 2016.

[124] F. P. Bowden and D. Tabor, *The friction and lubrication of solids* vol. 1: Oxford university press, 2001.

[125] E. Charlaix and M. Ciccotti, "Capillary condensation in confined media. handbook of nanophysics: Principles and methods. ed. klaus sattler," ed: CRC Press, 2010.

[126] D. S. Hecht, L. Hu, and G. Irvin, "Emerging transparent electrodes based on thin films of carbon nanotubes, graphene, and metallic nanostructures," *Advanced materials,* vol. 23, pp. 1482-1513, 2011.

[127] Y. Kawahara, S. Hodges, B. S. Cook, C. Zhang, and G. D. Abowd, "Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices," in *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*, 2013, pp. 363-372.

[128] *Ford, M. Can the 'silver bullet' of printing revolutionize electronics? Digital Biz, CNN, December 10th, 2009.* Available: http://edition.cnn.com/2009/TECH/12/09/electronics.printer.xerox/

[129] Dimatix *Dimatix Material Printer DMP-2831.* Available: http://www. fujifilmusa.com/products/industrial_inkjet_ printheads/deposition-products/dmp-2800/

[130] A. Mansour, N. Shehata, B. Hamza, and M. Rizk, "Efficient design of flexible and low cost paper-based inkjet-printed antenna," *International Journal of Antennas and Propagation,* vol. 2015, 2015.

[131] *Dimatix printer Fuji series price.* Available: https://www.labmakelaar.com/eng/detail/other/other-equipment/8405-dimatix-printer-van-fuji/8405

[132] *Dimatix Material Printer DMP-2831*. Available: http://www.fujifilmusa.com/products/industrial_inkjet_printheads/deposition-products/dmp-2800/

[133] B. S. Cook and A. Shamim, "Inkjet printing of novel wideband and high gain antennas on low-cost paper substrate," *IEEE Transactions on Antennas and Propagation,* vol. 60, pp. 4148-4156, 2012.

[134] A. R. Maza, B. Cook, G. Jabbour, and A. Shamim, "Paper-based inkjet-printed ultra-wideband fractal antennas," *IET microwaves, antennas & propagation,* vol. 6, pp. 1366-1373, 2012.

[135] S. Kim, Y.-J. Ren, H. Lee, A. Rida, S. Nikolaou, and M. M. Tentzeris, "Monopole antenna with inkjet-printed EBG array on paper substrate for wearable applications," *IEEE Antennas and wireless propagation letters,* vol. 11, pp. 663-666, 2012.

[136] S. Kim, Y. Kawahara, A. Georgiadis, A. Collado, and M. M. Tentzeris, "Low-cost inkjet-printed fully passive RFID tags for calibration-free capacitive/haptic sensor applications," *IEEE Sensors Journal,* vol. 15, pp. 3135-3145, 2015.

[137] G. A. Casula, G. Montisci, P. Maxia, G. Valente, A. Fanti, and G. Mazzarella, "A low-cost dual-band CPW-Fed printed LPDA for wireless communications," *IEEE Antennas and Wireless Propagation Letters,* vol. 15, pp. 1333-1336, 2016.

[138] V. Kale and D. Patil, "Antenna Simulation Tools and Designing of Log Periodic Dipole Antenna with CST Studio."

[139] *Agilent 85070E Dielectric Probe Kit 200 MHz to 50 GHz.* Available: http://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/centre-for-bio-inspired-technology/11949699.PDF

[140] I. Inc., "IEEE Standard Test Procedures for Antennas," ed: distributed by Wiley-Interscience, 1979.

[141] A. B. Constantine, *Antenna Theory,* Third Edition ed. USA: Wiley-Interscience, 2005.

[142] Y. Sun, S. W. Cheung, and T. I. Yuk, "Design of a textile ultra-wideband antenna with stable performance for body-centric wireless communications," *IET Microwaves, Antennas & Propagation,* vol. 8, pp. 1363-1375, 2014.

[143] P. B. Samal, P. J. Soh, and G. A. Vandenbosch, "UWB all-textile antenna with full ground plane for off-body WBAN communications," *IEEE Transactions on Antennas and Propagation,* vol. 62, pp. 102-108, 2014.

[144] P. J. Soh, G. A. Vandenbosch, S. L. Ooi, and N. H. M. Rais, "Design of a broadband all-textile slotted PIFA," *IEEE Transactions on Antennas and Propagation,* vol. 60, pp. 379-384, 2012.

[145] M. Klemm and G. Troester, "Textile UWB antennas for wireless body area networks," *IEEE Transactions on Antennas and Propagation,* vol. 54, pp. 3192-3197, 2006.

[146] J. Hautcoeur, X. Castel, F. Colombel, R. Benzerga, M. Himdi, G. Legeay, *et al.*, "Transparency and electrical properties of meshed metal films," *Thin Solid Films,* vol. 519, pp. 3851-3858, 2011.

[147] D. Corning. Available: http://www.dowcorning.com/applications/search/products/Details.aspx?prod=01064291

[148] D. C. Duffy, J. C. McDonald, O. J. Schueller, and G. M. Whitesides, "Rapid prototyping of microfluidic systems in poly (dimethylsiloxane)," *Analytical chemistry,* vol. 70, pp. 4974-4984, 1998.

[149] D. C. Duffy, O. J. Schueller, S. T. Brittain, and G. M. Whitesides, "Rapid prototyping of microfluidic switches in poly (dimethyl siloxane) and their actuation by electro-osmotic flow," *Journal of Micromechanics and Microengineering,* vol. 9, p. 211, 1999.

[150] S. Satyanarayana, R. N. Karnik, and A. Majumdar, "Stamp-and-stick room-temperature bonding technique for microdevices," *Journal of Microelectromechanical Systems,* vol. 14, pp. 392-399, 2005.

[151] G. Suresh and L. Jayakumari, "Evaluating the mechanical properties of E-Glass fiber/carbon fiber reinforced interpenetrating polymer networks," *Polímeros,* vol. 25, pp. 49-57, 2015.

[152] R. FANGUEIRO and F. SOUTINHO, "University of Minho, Portugal," *Fibrous and Composite Materials for Civil Engineering Applications,* p. 62, 2011.

[153] S. M. Lee*, Handbook of Composite Reinforcements*. USA: Wiley & Sons, 1993.

[154] A. composite. (2016). *Vacuum Infusion* Available: https://www.amtcomposites.co.za/sites/default/files/media/howto/Gurit%20Guide%20to%20Infusion%20Part%202.pdf

[155] G. Shaker, S. Safavi-Naeini, N. Sangary, and M. M. Tentzeris, "Inkjet printing of ultrawideband (UWB) antennas on paper-based substrates," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 111-114, 2011.

[156] "Synthesis and Simulation Converge in CST STUDIO SUITE," *Microwave Journals,* January 2015.

[157] F. Hirtenfelder, "Effective antenna simulations using CST MICROWAVE STUDIO®," in *Antennas, 2007. INICA'07. 2nd International ITG Conference on*, 2007, pp. 239-239.

[158] F. Demming-Janssen and W. Koch, "3D Field simulation of sparse arrays using various solver techniques within CST MICROWAVE STUDIOÂ®," in *Radar Conference, 2006. EuRAD 2006. 3rd European*, 2006, pp. 80-83.