12-2014

On the Development of Conductive Textile Antennas

Dounia Baiya
University of Tennessee - Knoxville, dbaiya@utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Dounia Baiya entitled "On the Development of Conductive Textile Antennas." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Aly Fathy, Major Professor

We have read this thesis and recommend its acceptance:

Syed Islam, Gong Gu

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

On the Development of Conductive Textile Antennas

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Dounia Baiya

December 2014

Abstract

UWB systems are becoming increasingly utilized due to their use in a variety of applications. Meanwhile, many advances have been achieved in the realm of conductive textiles. These textiles can be used as a sensing system or implemented wearable antennas. Combining these two applications is attractive for a number of reasons. First, wearable antennas constructed entirely from fabric offer a cost-effective, flexible solution when compared to rigid antennas. Second UWB technology is also attractive for body area network applications due to the low power operation and the inherent low radiated power in its system design.

In our implementation accurately defined textile antennas have been developed using a laser machine with high precision cutting capabilities. The textile antennas are comprised of a conductive fabric layer that is laser defined and can be easily incorporated into uniforms and garments using a simple iron-on process. We have developed and present a monopole antenna design geared towards UWB applications. We show that these UWB textile antennas can be applied to localization systems and can provide accurate estimation of wearers location.

Wide-band textile slot antennas have been developed too. The antennas are composed of three textile layers: the top and bottom are conducting layers and are precisely defined by a laser cutting machine, while the third layer is a textile dielectric layer sandwiched between these two conducting layers.

A single, two-element and four-element array slot antennas have been developed and successfully tested. The developed antennas offer flexible, light-weight and bendable

properties. The iron-on process allows for the fabric to be washed without losing its adhesion. The antenna fabrication and the capabilities of the laser precision technique and its extension to development of large area antenna arrays will be presented.
Conductive textiles can also be implemented to meet the requirements of combat wound detection systems. Using these textiles, a fabric-based sensor can be developed to accurately detect and localize the bullets penetration.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Using textiles for antenna development is an attractive option for many applications. Chief among these is the growing field of body area networks for narrow and ultra wideband applications. Ultra-wideband systems are becoming increasingly employed due to their use in a variety of applications. Similarly, many advances are being made in the realm of conductive textiles and flexible electronics. These textiles can be used as a sensing system or used to implement wearable antennas (10). Combining these two applications is attractive for a number of reasons. First, wearable antennas constructed entirely from fabric offer a cost-effective, flexible solution when compared to rigid antennas. UWB technology is also attractive for body area network applications due to the low-power operation and low radiated power inherent in its system design.

Utilizing textile antenna part of an RF system is very attractive and challenging in the same time. Because of its flexibility and low weight the antenna can be easily integrated into clothing. It can be used for medical applications for example: daily monitoring system for patient in home or hospital to sense and transmit vital signals like temperature, blood pressure or heart rate. It can be used also to track people for military application like tracking soldiers in the battle field or for civil application like to track a person diving or climbing a mountain. However there are many difficulties that a user of textile antennas can face. The small thickness of the fabric that insure its flexibility make the antenna hard to shape manually, the texture of the conductive fabric prevent soldering on it the light weight of the antenna make it very hard to test inside the anechoic chamber and so on.

In this thesis, we compare different textile antennas: materials, frequency of operation, applications ... we also present the design process of a UWB textile antenna for wearable applications. We offer fabrication suggestions to achieve tighter tolerances and higher accuracy greater than that achieved through manual means. Accurate localization is achieved using these antennas and a UWB localization system will be investigated. UWB antennas can be fabricated on thin layers of dielectric fabric, with thickness around 0.5 mm, to allow for easy integration into wearable applications.

This work was done in University of Tennessee with the help of Stephan Holland, we shared many background material. His work was more oriented toward Combat wound detection systems. It required to accurately detect the presence of bullet penetration. Knowing the time of impact, the number of penetrations and their locations in addition to evaluating numerous vital signs will allow the emergency medical team to quickly and accurately respond to find deployed soldiers. This response may come in the form of accurate instructions for local paramedics to treat a wound or by sending a rapid response medical team to perform injury treatments. My efforts were more into localization/tracking people wearing textile antennas using UWB localization system.

The organization of the these is as follows. In chapter 2, we discuss conductive textile antenna development and compare notes of some available structure of textile antennas. Chapter 3 approach materials and fabrication process. In chapter 4 we present the design and result of wideband textile slot antennas, one element, two and four element arrays. Chapter 5 discuss the design of an ultra-wideband monopole textile antenna development for UWB localization operating from 1-12GHz.

Chapter 2

Literature Review

2.1 Conductive Textile Antenna Development

Conductive textiles can be employed as a component in various communication systems development applications. For example there has been much research going on geared towards developing both on-body and off-body communication systems which utilize conductive textiles; where textile antennas are implemented for the purpose of transmitting or receiving signals collected from or sent to sensors or detectors. These textile antennas generally offer low-cost, lightweight, flexible alternatives when compared with their rigid counterparts. The key to textile antenna development is a two-fold. First, thorough characterization of the various fabric layers must be performed so that accurate simulation can be achieved. Second, fabrication requirements must be determined and prescribed so that precise structures can be manufactured and incorporated into textile antenna designs. Antennas can be developed using metalized textiles or by sewing conductive thread. In lower-frequency applications, many choose to incorporate the metalized textiles due to the larger size of the antenna. However, for high frequency applications, the antenna size is much smaller and a conductive thread can be tightly woven together with accurate antenna dimensions.

Numerous configurations of textile antennas such as monopoles, patches, and slots have long been sought for body area network applications and could easily be incorporated in combat wound detection systems. Sensors connected within the body area network can, ideally, send their information wirelessly via textile antennas incorporated directly into the clothing. Sugiyama et al. (15) describe this very idea in their development of a wearable, dual-band antenna. This antenna is unique to most in that it is designed to be placed on the ring finger. This alone restricts the maximum dimensions of antenna fabrication. They propose feeding their T-shaped monopole antenna with a 50 Ω coaxial cable. The dual-band nature of this antenna also enhances its operation as there is resonance between 2.4 GHz and 2.5 GHz as well as resonance from 4.5 GHz to 10 GHz (15). A wide variety of flexible, lightweight antenna configurations have been developed at lower frequencies other than those mentioned in (15). These configurations include patch designs, spirals, slots, and monopoles. For example, Galehdar (16) presents a linearly polarized rectangular patch antenna for incorporation into athletic uniforms and clothing. The draw for incorporating antennas into athlete clothing is substantial and can easily be extrapolated to militaristic avenues. Galehdar mentions the desire for coaches to have information useful in making tactical changes during a sporting event. With knowledge of how an athlete is performing bio mechanically and physiologically, these changes can be accurately made. Gain is also an important characteristic for these antenna designs so that the battery size can be decreased while the range can be large enough for the event. Galehdar designs a patch antenna operating at 2.45 GHz with thickness 1.6 mm and relative permittivity of 1.63. He investigates the effects of bending in both the E and H planes. Determined experimentally, increasing the radius of bend decreases the resonant frequency in the E plane of the patch antenna. Similarly, the resonant frequency increases for positive bending angles and decreases for negative bending angles in the H plane. The maximum change in frequency for both planes is 8 % (16). For wideband antenna design, this change in resonant frequency is largely negligible. However, for narrow- band resonance, special care must be taken in the design of flexible, textile antennas to ensure the changes in frequency of operation are acceptable throughout the bending and maneuvering of the antennas. Depending on its use, antenna design may need to account for these bending effects. For localization applications demonstrated in this thesis, wideband antennas are used and will be less susceptible to bending as a result of their wideband nature. However, wireless transmission at Wi-Fi frequencies could be affected by this property.

Shimasaki [(17), (18)] also investigates the effects of bending on conductive textile antennas. He performs studies on a cavity-backed slot antenna bent along a spherical surface. The antenna developed to complete these studies has thickness of 2.5 mm and area of 95 mm x 90 mm and is created from conductive threads. The slot is realized by removing the conductive threads in the appropriate areas The operation frequency of this antenna is around 2.3 GHz.

(18), Shimasaki reports the effects of bending along a spherical surface. The radius of bending along the spherical surface of this antenna is 200 mm For the planar antenna, the bandwidth of the designed cavity-backed slot is 230 MHz as compared to a decreased bandwidth of 162 MHz for the bent case. The center resonance frequency also decreases by 84 MHz (17). This down-shift in frequency is similar to the results presented by Galehdar. The radiation patterns differ slightly from the planar and bending scenario. The shape of the pattern remains similar though a slight decrease in directivity amplitude is visible. One potential source of inaccuracies in this design comes from the repeated bending and flexing of the cavity-backed slot antenna. This repeated motion could affect the dimensions of the cavity by producing thickness fluctuations over time.

In addition to the metalized fabric used for many antenna applications, some designers choose to, instead, weave metalized fibers into fabrics in the appropriate antenna shape. Morris et al. (4) proposes the use of metalized, high-strength Kevlar for conformal load-bearing antenna applications. These antennas can be of use for applications involving unmanned aerial vehicles (UAVs) due to their conformal, lightweight, and damage-resistant (high-strength) properties. Morris points out that, in some cases, the frequency of communication coupled with the small size of some UAV models forces the entire chassis to be used as the antenna. This places even more importance on a lightweight, durable antenna design. To meet these design requirements, Morris metalized Kevlar fibers and wove them into broadband antenna designs. This manual weaving of metallic thread is risky; if the thread were to break, the antenna would prove useless. Morris designed and fabricated a broadband spiral antenna also on a polymer-ceramic composite meant for RF applications. This dielectric, polydimethylsiloxane (PDMS), has the flexibility required to meet the antenna design specifications (thickness of 4 mm) while offering a tunable permittivity up to 20 and a loss tangent less than 0.01. Its electrical properties are similar to those of the Rogers TMM4. The broadband spiral antenna is designed to work from 200 MHz to 1000 MHz and can be seen in Fig. 2.1. The substrate was drilled using a 50 W laser to etch patterns for the fiber to be woven. The metalized yarn was then manually woven through the substrate using a sewing needle. They found that weaving the yarns created a gradual increase in the wire resistance and attribute this to the deterioration of the metal film under cyclic flexing and torsion (4). It is possible that, due to consistent flexing over time, antennas created by this technique will not continue to function correctly. While it is not the Kevlar that is suspect to fail, the metalized coating could wear off under repetitive stress. This is the primary challenge that faces the development of textile antennas using singular conductive threads. Further analysis would be necessary to determine the expected lifespan of an antenna created by weaving metalized threads. While the measured return loss matches decently with the test antenna printed on Rogers TMM4 at frequencies greater than 600 MHz, the realized gain measurements are dissimilar until approximately 750 MHz. At lower frequencies, the realized gain of the woven antenna is far inferior to the realized gain produced by the traditionally fabricated antenna. They attribute these inconsistencies to improper input matching at lower frequencies. As mentioned above, conformal, load bearing antennas are an attractive option for UAV applications.

These antennas are critical for low frequency communication applications in these scenarios. To ensure durability while maintaining beneficial characteristics such as flexibility and low weight, Wang et al. (8) chose to adapt a multilayer approach to antenna fabrication. This approach utilizes lightweight, low-loss materials such as polymers as a dielectric for the textile antennas. Like the work completed by Morris et al., Wang chooses PDMS as the flexible dielectric for his patch antenna designs. Also like Morris, Wang (8) employs conductive thread to weave a patch antenna on his multilayer surface. Amber strand silver-coated Zylon fibers with resistance of 0.8 Ω/m were used as this conductive thread. This envisioned multilayer surface is depicted in Fig. 2.2. To test this new conductive fiber, a 31 mm x 31 mm probe fed patch was developed and placed on the PDMS substrate. This antenna was designed to resonate at 2.2 GHz. Compared to a simulated version of the same design, the fabricated textile patch antenna gain was only 0.2 dB lower. This corresponded to a textile antenna gain of 5.7 dB. It is evident that these textiles can be implemented in antenna designs to provide a reliable, flexible solution to the UAV communication application. In addition to their aforementioned use in wireless body area networks as well as load-bearing applications, textile antennas are also a popular alternative in ultra- wideband (UWB) applications. Klemm and Troester (10) develop a textile UWB antenna for wireless body area networks. They claim that their antennas offer direct integration into clothing due to their thinness and flexibility. They realize two different types of textile antennas: a coplanar-waveguide-fed disc monopole and an annular slot antenna. These designs operate in the entire UWB band, 3.1 GHz to 10.6 GHz, approved by the Federal Communications Commission. Each utilizes conductive textiles with very high conductivity. This metalized Nylon fabric created by Shieldex has surface resistivity of 0.03 Ω/sq. As the dielectric substrate, they use an acrylic fabric with thickness of 0.5 mm. The permittivity of this dielectric was found to be 2.6 0.1 over the frequency band of interest. As important as the fabric selection is the antenna fabrication. The antenna must be fabricated in such a way as to retain the correct antenna dimensions while also preventing a change of the electrical

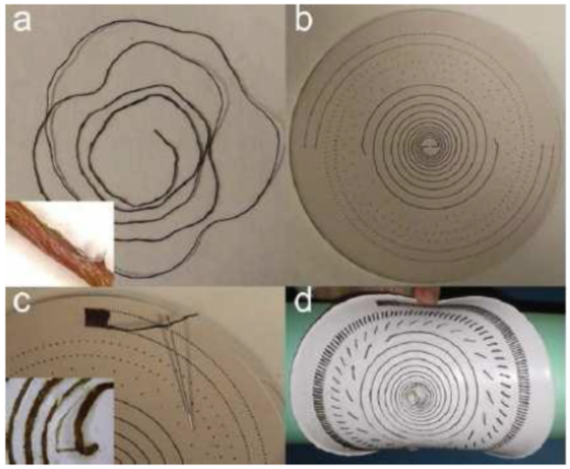


Figure 2.1: Broadband Spiral Antenna Implemented after (4).

properties. Klemm uses adhesive iron-on sheets to achieve this goal. These sheets merely deposit a thin adhesive layer on the textiles such that the sheet resistance and permittivity parameters are not altered. An SMA connector was attached to the antenna using a two-part conductive glue. (10) Difficulties exist in using textiles to implement antennas. As Klemm points out, it is difficult to implement CPW technology through manual means. They use a scalpel to realize the small widths between the ground plane and the signal. This is a very difficult task. In their fabrication process, they achieved a characteristic impedance of 59 Ω. As you can see, this is not a perfect match to a 50 Ω system. For textile antennas to become more accurate, the fabrication process must be addressed and higher accuracy be achieved. At low frequencies, up to 8 GHz, the textile antennas agree well with traditional printed circuit board (PCB) antennas. Above 8 GHz, however, the losses of the textiles outweigh those of traditional PCB antennas. However, it is evident that these antennas are a viable option for UWB systems. The received pulses of a two-antenna system with textile antennas match nearly perfect with the PCB antennas.

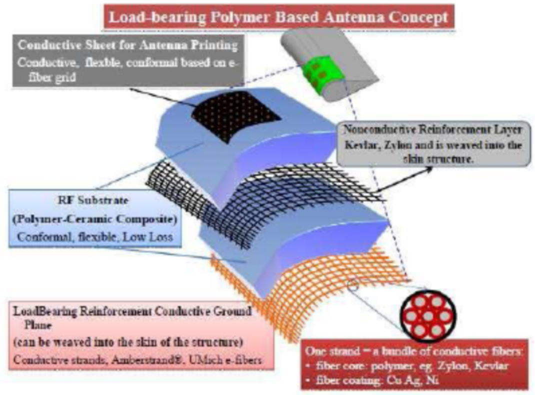


Figure 2.2: Multilayer Textile Antenna for Integration into UAV Body after (8).

2.1.1 Body Influence on Antennas Performance

Klemm also investigates the influence of the body on the UWB antennas. As the antenna moves closer to the body, the normalized amplitude of the transmitted pulse decreases. Interestingly, when the antenna is 6 mm from the body, the transmitted pulses are higher in amplitude than the transmitted pulses in free space. Klemm and Troester attribute these results to indication that the body constructively reflects electromagnetic waves at frequencies greater than 4.5 GHz. Giddens (1) investigated the influence of the body on wearable antenna efficiency. With this information, it is hopeful that more efficient antennas could be developed for use in body area network applications. This study analyzes the reflection coefficient of the antenna at different distances away from the body. They confirm through simulation and measurement that no significant detuning occurs as a result of proximity to the phantom. While increasing the ground plane of the patch antenna did not alter efficiency, their study shows that a 75% increase in efficiency can be obtained by spacing the antenna away from the body. In Table 2.1, data was reproduced from their presentation to describe the increase in efficiency seen as the distance between the body and patch antenna was increased. Similar results were obtained through other studies performed by Zhu (5), Klemm (10), and Thompson (19). Instead of increasing the distance from the body to improve efficiency, Zhu (5) incorporates the antenna over an electromagnetic band gap structure. Klemm (10) illustrates the differences between on-body and off-body communication, while Thompson (19) focuses his efforts on the antenna mounting method and how that can be altered to improve the correlation coefficient of body worn antennas reflection coefficients on and off the body (19). Substrate integrated waveguide technology has also been introduced to textile antenna development to improve the bandwidth and input matching characteristics of the antenna and eventually can be used for long low loss transmission lines embedded on the fabric. Moro (6) designs a cavity-backed dog-bone slot antenna in substrate integrated waveguide technology. There are numerous benefits for utilizing the cavity for textile antennas to be used in on-body communication applications. These include a suppression of surface waves, lower sensitivity to body proximity, and high front-to-back ratio (20). The substrate used to fabricate this antenna is a protective foam typically incorporated into firefighter uniforms. It has a thickness of 3.94 mm, permittivity of 1.575 and a loss tangent of 0.0238 at 2.45 GHz. The top and bottom conductive textile layers employ Flectron with surface resistivity of 0.18 Ω/sq at 2.45 GHz. The substrate integrated waveguide technology is realized by perforating the antenna and placing metal eyelets in each of the holes. These eyelets are 7 mm in diameter and are spaced 14 mm apart. The complete antenna fabricated by Moro is shown in Fig. 2.3. The Flectron sheets are the copper colored sheets in Fig. 2.3. This antenna was tested stand-alone and resonates at 2.45 GHz with broadside gain of 3.9 dBi measured (compared to 3.21 dBi simulated). It was again tested after integration into the backside of a firefighter uniform between the waterproof and moisture/thermal barrier layers. The body proximity does not affect this antenna as the resonant frequency is negligibly decreased and the radiation patterns generate the same approximate shape. It is worthwhile to note, however, that Moro reports a measured broadside gain of 4.9 dBi during the on-body test. This increase is attributed to the wider ground plane caused by the presence of the body (6). The use of substrate integrated waveguide technology in textile antenna design could be

Table 2.1: Effect of Increasing Distance Between Body and Textile Antenna on Antenna after (1).

Number of felt layers	Measured Efficiency ±5%	Maximum Measured Radiated Power (dB)
0	29	-2.3
1	33	-2.6
3	33	-1.5
5	46	-1.1
7	51	0

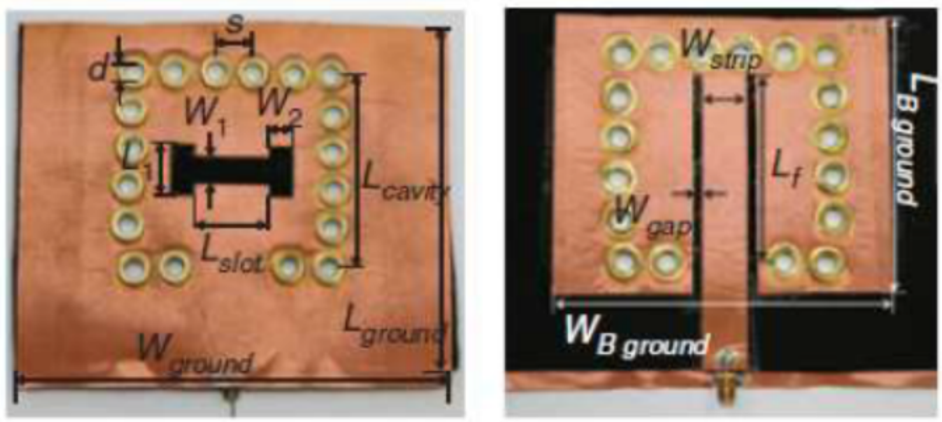


Figure 2.3: Substrate Integrated Waveguide Cavity-Backed Dog-Bone Slot Antenna after (6).

useful to improve the on-body characteristics as compared to antenna development neglecting the effects of body proximity.

2.1.2 Issues to be Considered when Using Fabrics

Textile materials generally have a very low dielectric constant, which reduces the surface wave losses and improves the impedance bandwidth of the antenna relative to antennas with high dielectric substrates, textile antennas are physically larger.

In general, there are main issues that need to be addressed in the design of these textile antennas:

Elastic properties of textile materials:

The variation of dimensions due to stretching and compression are typical for fabrics. This dimensions changes could lead to changes in the resonant length of the antenna and detune its frequency band while the substrate thickness changes the resonant frequency as well as the input impedance bandwidth. So, it is desirable to avoid elastic fibers.

Wetness:

If the fabric absorbs water, then its dielectric constant will change dramatically, as the dielectric constant of water is much higher. When a fabric antenna absorbs water, the moisture changes the antenna performance parameters dramatically and it will reduce its resonant frequency. Fabric antennas can absorb sweats or rain if placed on top of jackets. Hence, some sort of buffer layers can be used to eliminate such effect.

Bending:

In general, wearable antennas cannot be placed on flat surfaces especially in places like sleeves where bending is expected to occur. Bending could affect the resonance length of antennas; especially if it is a narrow band antenna.

Vicinity of Human Body:

Antennas performance will change significantly when placed next to the human body. In addition, they should be tested for their radiation levels. They should be designed taking the effect of human body, limited ground plane. In addition, special attention must be paid to the Specific Absorption Rates (SAR), which aids in the quantitative study of power absorption issues required to meet the standards in order to avoid harm to human body. Thus, in the vicinity of the human body, several issues should be considered such as antenna input-match performance, radiation characteristics of the antenna, and the power absorbed in the human body.

Human Body Movements:

If the body is moving too, it will have an impact on the antenna characteristics and should be accounted for as signals will be affected from local scattering. Human body is subject to many small movements even when standing, sitting, during normal activities, and even during playing of sports.

2.2 Available Structure of Textile Antennas

2.2.1 Narrow Band Textile Antenna

Electro-Textile Patch Antenna

Electro-textiles are conductive fabrics constructed by interpolating conductive metal / polymer threads with normal fabric threads or conductive threads. These fabrics are considered a strong candidate to be integrated into clothing for distributed body-worn electronics because they are washable, durable and flexible.

As an example (2) two electro-textile patch antennas fabricated and tested using a Satin 5 woven fabric as the top layer. They also fabricated a reference copper patch antenna, on the same dielectric substrate with thickness of 3.175 mm (Rogers Duroid 5880). Coax feeds from the back of the patch antennas was used, see Fig. 2.4. Of the two electro-textile antennas, one is with the metallic face (the side with more conductive threads) facing against the substrate; the other one is with the fabric face (the side with more non conductive thread) facing against the substrate; the other one is with the fabric face (the side with more non conductive thread) facing downwards. The asymmetry on both faces of the satin weave electro-textiles results in different dielectric loss in the fabric material depending on the placement of the fabric on the substrate. The same effect is expected on the antenna loss mechanism which relates to the efficiency of the patch antenna.

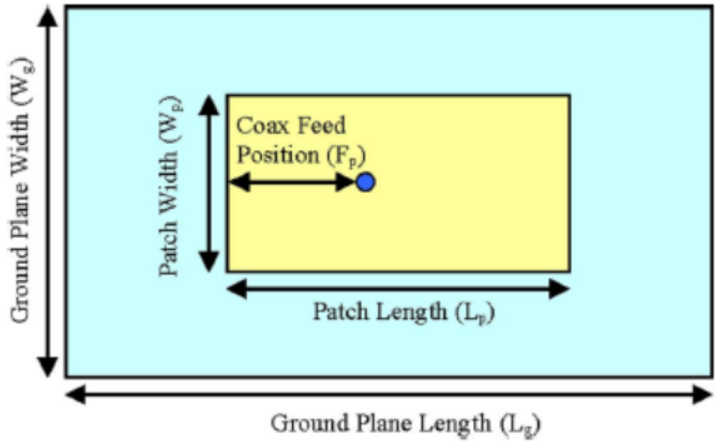


Figure 2.4: Sketch of Rectangular Patch Antennas after (2).

Table 2.2: Dimensions of Test Electro-Textile Patch Antennas (milimeters) after (2).

	L_g	W_g	L_p	W_p	F_p
Reference Copper Patch Antenna	102	63	40	26	15
Electro–textile Patch Antenna (metalic)	116	77	39	27	15.5
Electro–textile Patch Antenna (fabric)	116	77	38.5	27	15.5

The dimensions for all three antennas (listed in Table 2.2) are very close to each other except for the size of the ground plane which is sufficiently large. The resonant frequencies of the three antennas match with each other (Fig. 2.5). This means that though electro-textiles have periodic conductive structure on a microscopic scale, they behave like continuous metal laminates with various effective conductivity. The performance of the three antennas is summarized in Table 2.3

Table 2.3: Test Electro-Textile Antenna Performance(2.44 GHz) after (2)

	Gain (dB)	Efficiency (%)	Bandwidth (%)
Reference Copper Patch Antenn	7.4	95	2.2
Electro-textile Patch Antenna (metallic)	7.1	88	2.6
Electro-textile Patch Antenna (fabric)	6.6	79	2.9

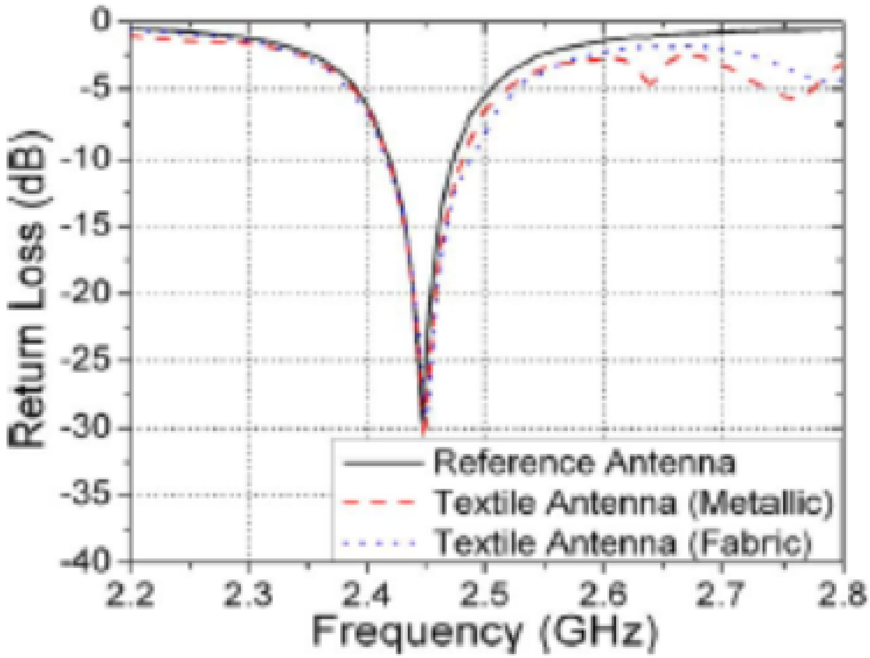


Figure 2.5: S11 of the Reference and Electro-Textile Patch Antennas after (2).

Dual-Band E-Shaped Patch Wearable Textile

The wearable textile antenna proposed in (9) is designed for 2.2 GHz and 3.0 GHz frequencies. Fig. 2.6 shows the geometry and dimensions of the measured E-shaped patch antenna mounted on the top surface 4 mm thick felt fabric. The measured relative permittivity of the substrate is 1.1. The conducting surfaces are made out of copper tape. The antenna arm length determines the lower resonant frequency which is approximately half wavelength at the lower resonant frequency. The length of the inner arm and slot dimensions affect the upper resonant frequency. Fig. 2.7 shows the simulated and measured return loss of the antenna. The bandwidths are 100 MHz and 110 MHz for the lower and upper frequency bands, respectively. Simulated and measured radiation patterns are shown in Fig. 2.8 and Fig. 2.9 respectively, for both center frequencies. Measured and simulated radiation patterns demonstrate reasonable similarity.

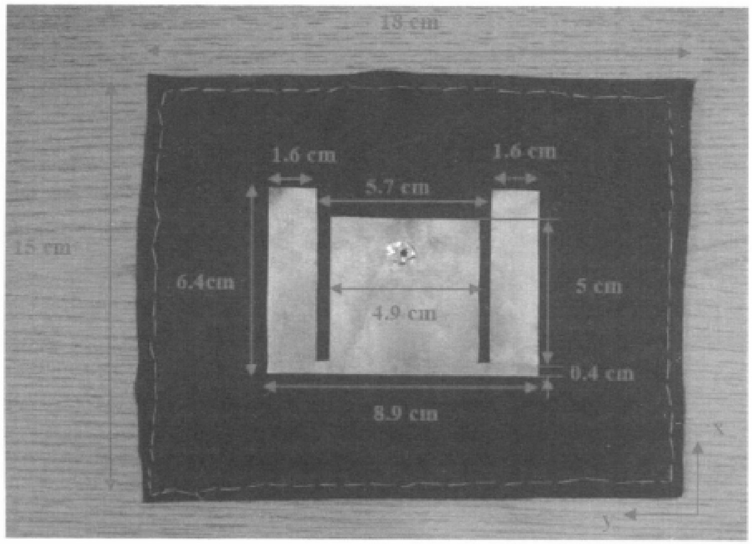


Figure 2.6: Photo of Constructed and Measured Dual-Band E-Shaped Textile Antenna after (9).

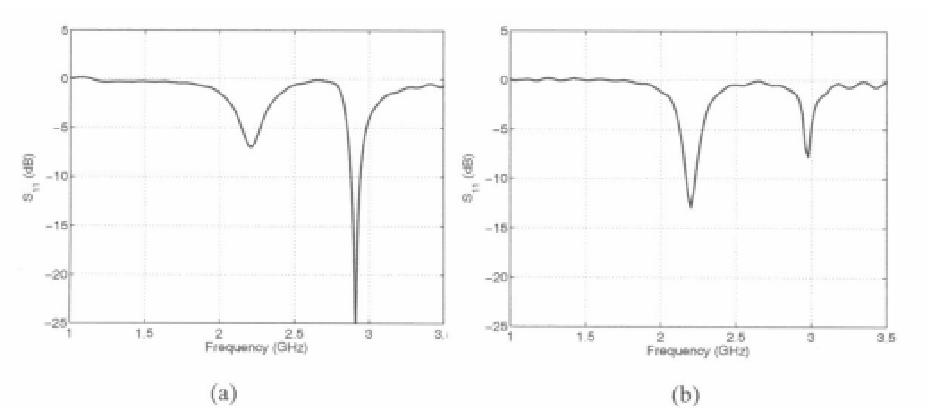


Figure 2.7: Retum-Loss Characteristics of E-Shaped Patch Antenna. (a) Simulated S11 (b) Measured S11 after (9).

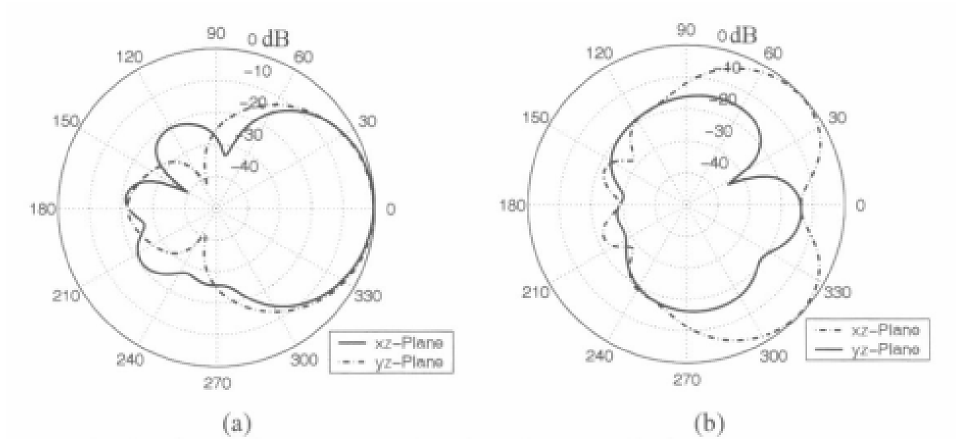


Figure 2.8: Simulated Radiation Patterns of E-Shaped Antenna in Free Space. (a) Freq. = 2.2 GHz. (b) Freq. = 2.9 GHlz after (9).

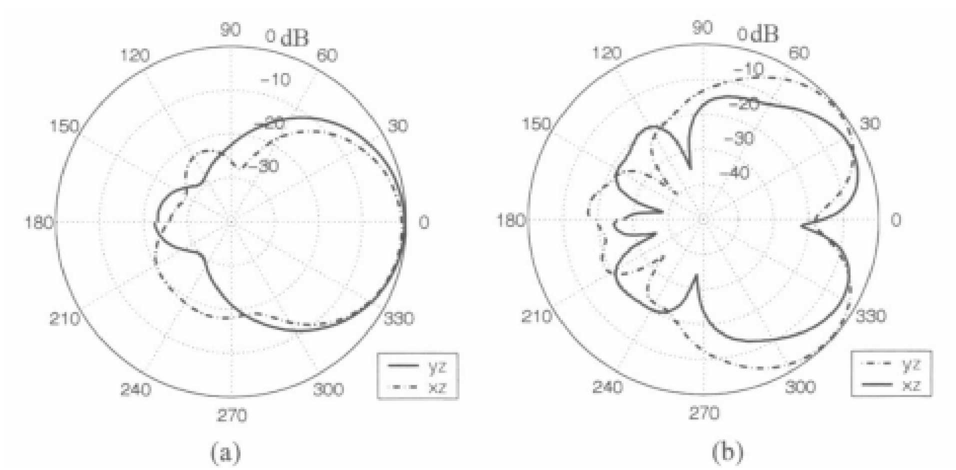


Figure 2.9: Measured Radiation Patterns of E-Shaped Antenna in Free Space. (a) Freq. = 2.2GHz. (b) Freq. = 3.0 GHz after (9).

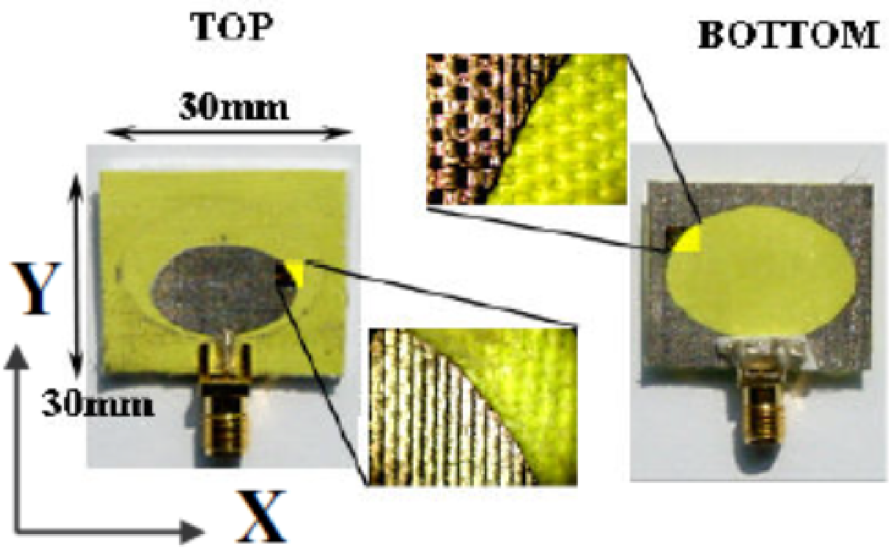


Figure 2.10: Textile UWB Annular Antenna after (10).

2.2.2 UWB Textile Antennas

Annular Slot Textile UWB Antenna

In (10) the author describe an annular slot textile UWB antenna used for on body communications. As Conductor material this group used high conductive metalized Nylon fabric-Nora. Its three metalized layers (Ni/Cu/Ag) provide high conductivity (surface resistivity of 0.03 Ω/sq). They chose an acrylic fabric of 0.5 mm thick as a dielectric substrate. The permittivity of the substrate is 2.6 (+/-0.1) between 3 and 10 GHz.

Fig. 2.10 illustrates the designed UWB annular slot antenna. The antenna is fed by a short microstrip line. The size of the antenna is 30x30 mm^2.

Fig. 2.11 presents a comparison between the measured and simulated return loss characteristics. To have an idea about the repeatability of the antenna manufacturing, The group also has built two prototypes (S1, S2) of the same design. The antennas are hand-made. Antennas have good input matching below -10dB, measured and simulated results agree well.

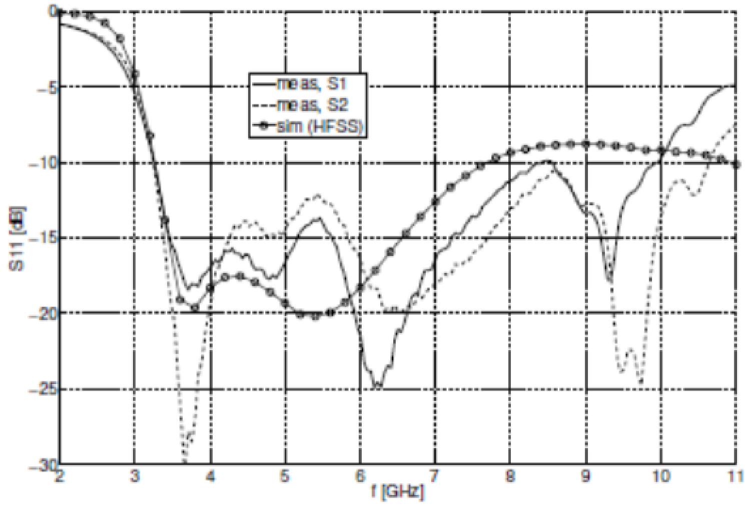


Figure 2.11: Measured and Simulated Free-Space Return Loss Characteristics S1 and S2 are Two Antenna Prototypes Manufactured for Reliability Check after (10).

Circular UWB Wearable Antenna

In (3) different structures have been designed and analyzed, circular UWB antenna with small radius (Antenna #1), circular UWB antenna with large radius (Antenna #2) and annular UWB antenna (Antenna #3). A partial ground plane was implemented in all antenna designs. Fig. 2.13 illustrate the simulated models.

The conductive surfaces and the ground plane of all three designed antennas are made out of copper tape with a thickness of 0.03 mm. The author planned to cover the feed line of all antenna designs by another layer of jeans fabric. The reason behind this, that those antennas were intended to be mounted or embedded in a wearable jacket or suit. Table 2.4 shows the proprieties of the jean fabric used as substrate. The second layer of jeans fabric was placed on the top of the microstrip feed line with an air gap of 1 mm thickness. This air gap was implemented in the simulation part as well as the fabrication process.

Antenna Dimensions

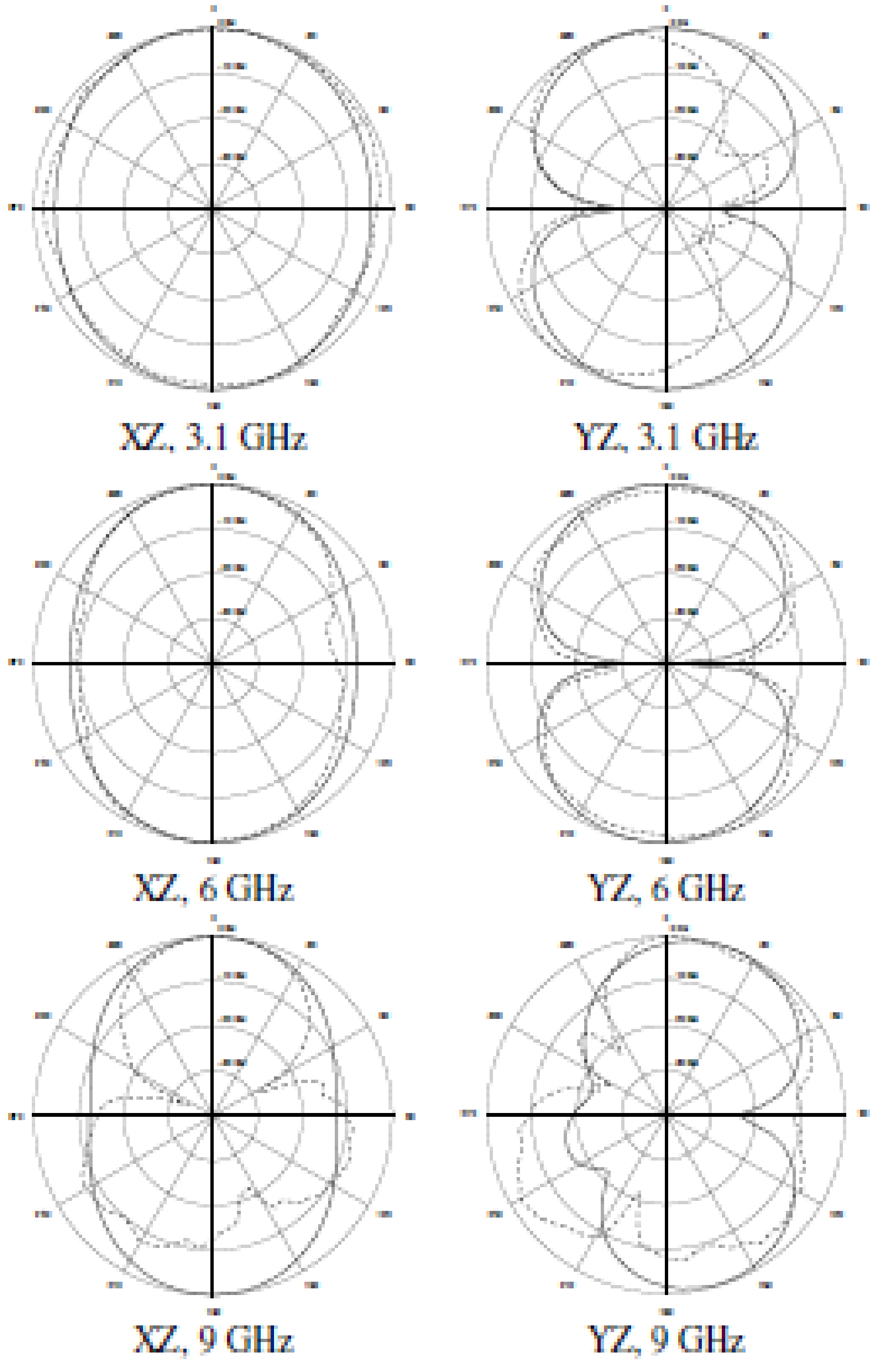


Figure 2.12: Measured and Simulated Free-Space Radiation Patterns after (10).

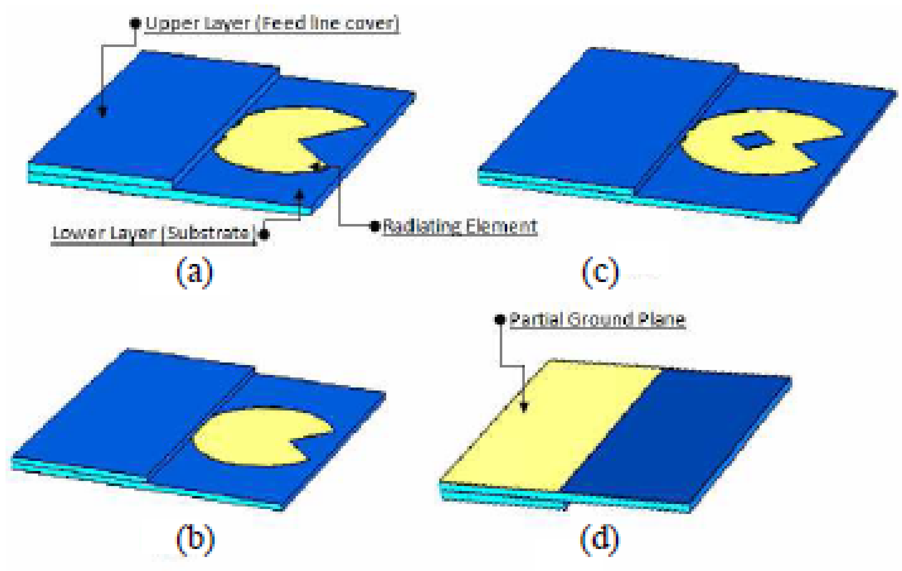


Figure 2.13: CST Simulation Design Models. (a) Top View of Antenna #1. (b) Top View of Antenna #2. (c) Top View of Antenna #3. (d) Back View of Partial Ground Plane after (3).

Table 2.4: Fabric Thickness and Measured Relative Permittivity of Jeans Substrate Textile Material by Implementing the Free Space Method after (3).

Material	Value
Thickness, $h(mm)$	1
Measured relative permittivity, ϵ_r	1.7
Loss Tangent	0.025

Table 2.5 illustrates the dimension of all antennas presented in (3). Also Fig. 2.14 demonstrates the geometry of those antenna prototypes mounted on the surface of jeans textile substrate material.

Results and Discussions

Fig. 2.15 shows a comparison between simulated and measured results in terms of return loss and bandwidth of the three antennas. The black solid line demonstrates the simulated results, while the blue dotted line shows the measured results. The measured results showed that it does agree very well with simulations and a wideband range of frequencies between 3 GHz and 12 GHz was covered by this design.

Table 2.5: Dimensions of the Three Antennas in Millimeters after (3)

	Patch radius (mm)	Substrate dimensions (mm)	Partial ground plane (mm)	Air gap (mm)	Over all thickness	Center square slot (mm)
Antenna #1	11	40 x 40	40 x 20	1	2.6	-
Antenna #2	15	60 x 60	60 x 29	1	2.6	-
Antenna #3	15	60 x 60	50 x 29	1	2.6	6x6

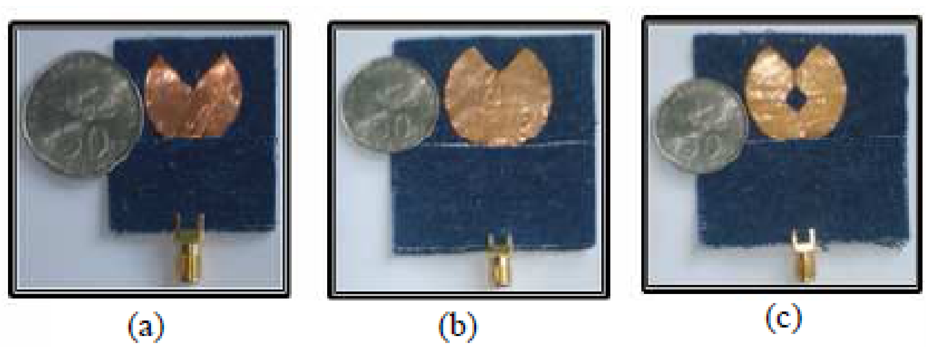


Figure 2.14: UWB Antenna Prototypes. (a) Antenna #1, UWB Wearable Antenna with Small Radius. (b) Antenna #2, UWB Wearable Antenna with Large Radius. (c) Antenna #3, UWB Wearable Antenna with Center Hole after (3).

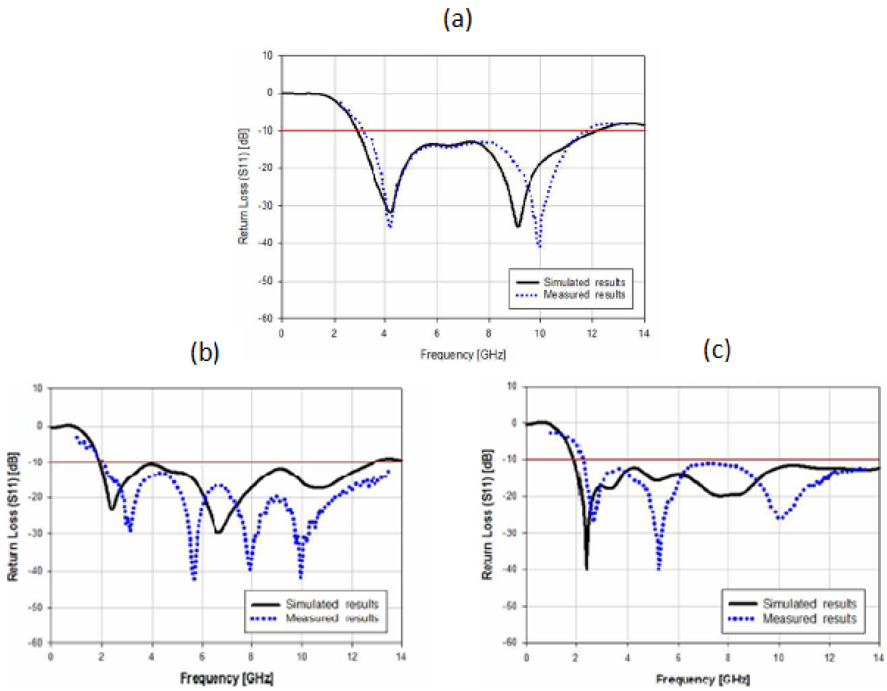


Figure 2.15: Simulated and Measured Return Loss Results of (a) Antenna #1, (b) Antenna #2 and (c) Antenna #3 after (3).

Textile Patch Antenna

Techniques of Fabrication

In (11) the group investigated four different techniques to fabricate a microstrip patch antenna.

Copper Foil: The simplest of the methods and it involves the application of commonly available copper tapes that can be directly applied to the substrate of interest (in this case textile fabrics) with no extra fabrication processes.

Copper Mesh: In this technique, copper thread is woven into the textile substrate which offers more stable and rigid structure comparing to the copper taper method.

Conductive spray: A spray with a mixture of copper with gases under pressure can be used to obtain a conductive layer in the surfaces of the textile exposed to the spray. This method provides flexibility and reliability for general textile antenna design.

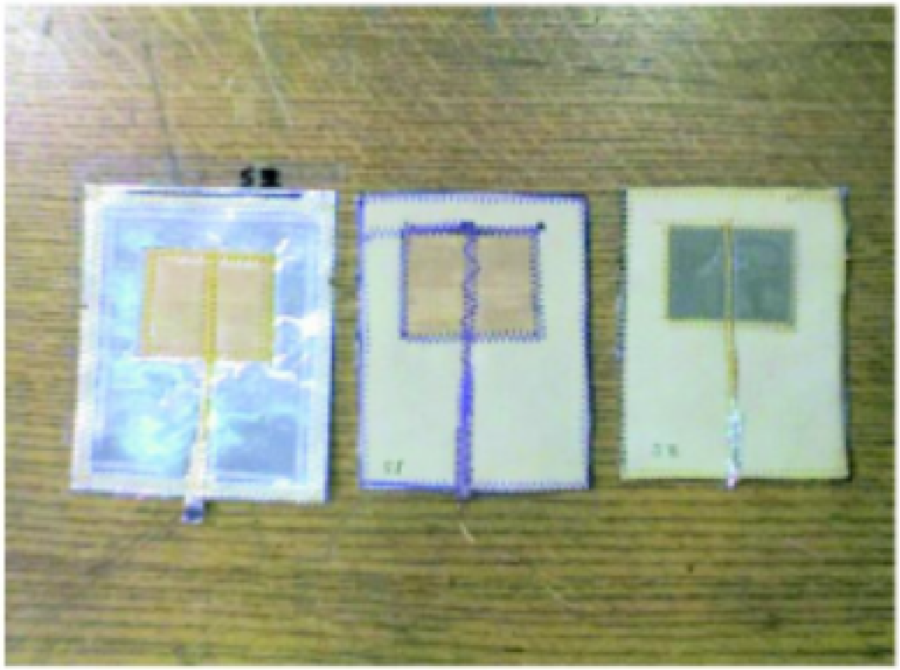


Figure 2.16: Fabricated Textile Patch Antennas. From Left to Right; Applying Copper Tape, Woven Copper Thread and Conductive Spray after (11).

Copper with rubber: Mixture of conductive nano-particles and rubber to produce flexible and rigid conductor layers to be applied in textile antenna and general textile electronic structures.

Fig. 2.16 illustrates fabrication of the textile patch antenna using the first three techniques described earlier. The textile antenna fabricated applying woven copper thread has a leather substrate with relative permittivity of Er=2 and conductivity of 0.001 S/m. The antenna performance is investigated for both free space and on-body cases.

Results and Discussions

Fig. 2.17 illustrates the frequency resonance in free space (3.2 GHz) which shows the effect of changing on-body positions and also the flexible substrate on antenna performance which directly affects radiated power level and hence the reliability of the communication link. Fig. 2.18 demonstrates the measured radiation patterns of

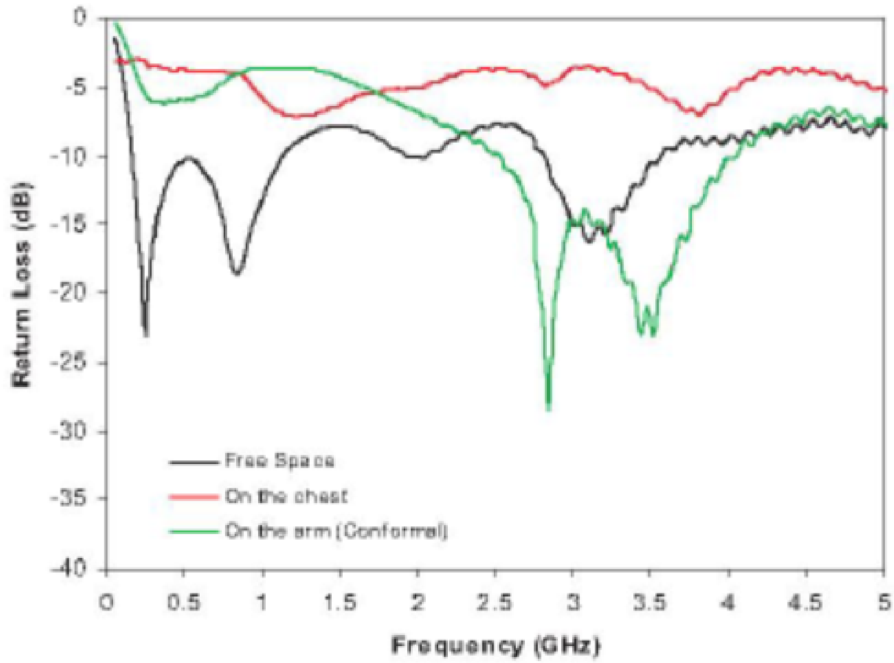


Figure 2.17: Return Loss (S11) of the Fabricated Textile Antenna when Placed in Free Space and on the Body (Chest and Conformal to the Arm) after (11).

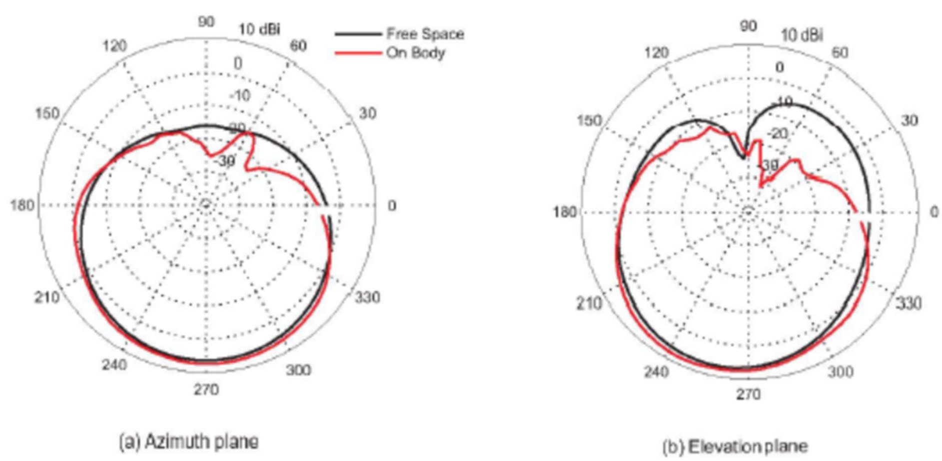


Figure 2.18: Radiation Patterns of the Fabricated Textile Microstrip Patch Antenna when Placed in Free Space and on the Human Chest after (11).

the fabricated textile patch antenna (using woven copper thread) for both stand-alone and on-body scenarios. Due to the presence of antenna shielding represented by the backside ground plane, the antenna radiation performance is not significantly chan ged specifically from front-to-back ratio and main radiation beam prospective.

2.2.3 Conclusion

Many techniques have been developed to define the textile antennas but they are mostly manual and typically result in inaccuracies in the fabrication process. All the antennas described earlier in this chapter are summarized in Table 2.6
The use of textiles for wearable applications offers a low-cost, flexible solution when compared to rigid antennas. This flexibility becomes even more important when large arrays are required. In Ch: 3 new technique of fabrication will be presented. In order to confirm the reliability of the method many antennas were designed built and tested.

Table 2.6: Antenna Summary

Textile Antenna	Conductive Material	Dielectric	Size (mm)	F (GHz)	Fabrication	Application	Challenges
Cavity-Backed Slot (18)	Conductive Threads	NA	95x90	2.3	Manually	NA	NA
Broadband Spiral (4)	Metalized Kevlar	(PDMS)	NA	0.2-1	50W Laser/Sewing Needle	RF	Thread Break Risk
Patch Antenna (8)	Amber Strand Silver-Coated Zylon Fiber	PDMS	31x31	2.2	Multilayer Fabrication	UAV Com.	NA
Coplanar-Waveguide-Fed Disc Monopole (10)	Metalized Nylon Fabric	Acrylic Fabric	NA	3.1-10.6	Manually	WBAN	Hard Manual Fab.
Cavity-Backed Dog-Bone Slot (6)	Flectron	Protective Foam	NA	2.45	Metal Eyelets are Placed Manually	On-Body Com.	Not Flexible
Electro-Textile Patch (2)	Satin 5 Woven	Rogers Duriod 5880	NA	2.45	Manually	NA	Not Flexible
Eual-Band E-Shaped Patch (9)	Copper Tape	Felt Fabric	64x89	2.2,3	Manually	NA	NA
Annular Slot (10)	(Ni/Cu/Ag)	Acrylic Fabric	30x30	3-10	Manually	On-Body Com.	NA
Circular UWB (3)	Copper Tape	Jeans Fabric	60x60	3-12	Manually	NA	NA
Patch Antenna (11)	Cu foil, Mesh	Leather	Na	3.2	NA	On-Body Com.	NA

Chapter 3

Materials and Fabrication

Conductive textiles can be made of woven metal threads or can be formed through a process known as metallization. In comparison, the metalized textiles are much more durable and flexible.

3.1 Metallization Process

Conductive textiles can be created through a process known as metallization. Metallization is a process in which a fabric or some other solid can be coated with a thin layer of metal. Different materials can be coated through various metallization techniques. Metallization of fabric can occur on two scales; either the individual thread can be metalized prior to being woven or a finished fabric can be metalized to coat the entire surface at once.

Four metallization techniques are common: vacuum deposition, ion plating, electroplating, and electroless plating. The most common techniques used to create conductive textiles are electroplating, also known as electrode position, and electroless plating. Electroplating is a process that utilizes electrical current to deposit a layer of metal particles on a material. Metals such as alloys, chromium, copper, gold, nickel and silver can be deposited on fabric surfaces by using the electroplating process. An example for electroplating system is shown in Fig. 3.1. In this system, the sample material is connected to the cathode while the anode contains the metal to be deposited on the fabric. In the presence of an electrical current, metallic ions travel through the plating solution and are deposited on the fabric material.(21)

A thorough description of the other common metallization technique, electroless plating, is presented in (21). Electroless plating is a non-galvanic technique that involves several simultaneous chemical reactions in an aqueous solution occurring without the use of external electric current (21). Ionization occurs when hydrogen is released by a reducing agent and produces a negative charge on the surface of material following oxidization. This method enables the metal coating of non-conductive textile materials. A uniform metallic layer can be achieved with this method due to the lack of an electric field. This technique is commonly used to bond a metallic nickel base layer to a textile prior to re-coating with a more conductive metal such as silver or gold. Little and his team (22) show the capability of metallizing Kevlar fibers with gold using an electroplating method as well as an electroless method. Many commercially available conductive textiles are created through this or a similar metallization process. One challenge with conductive textile fabrication is ensuring an even coating of the fabric. This is a crucial parameter as uniformity of the metallization becomes paramount in communication system component design. Fig. 3.2 depicts a conductive textile sample under intense magnification. This image shows the capability of the metallization process to evenly coat all parts of the textile providing uniform conductivity throughout.

Many vendors market conductive textiles. A few of these vendors include LessEMF.com, Swift Textile Metallizing, LLC, Marktek, Inc., Shieldex, and Metal Textiles Corporation. Each of these companies mainly advertises the use of conductive textiles for shielding applications. A number of potential conductive textiles can be found in the conductive textile tables in the Appendix of this thesis. These tables compare various properties of conductive textiles based on vendor such as, fabric type, fabric thickness, metallic coating and shielding effectiveness. Fig. 3.3 illustrates a wide variety of conductive textiles that can be purchased.

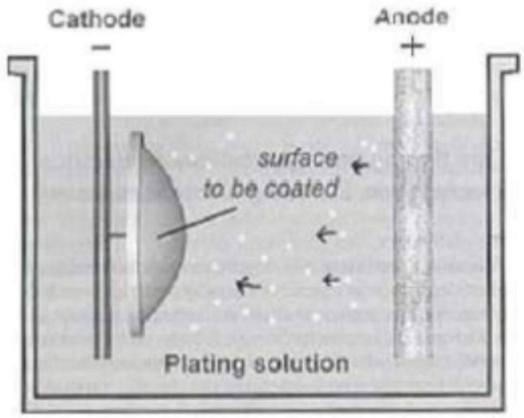


Figure 3.1: Electroplating (Electrode Position) Technique that Could be Used to Metallized a Fabric, after (12).

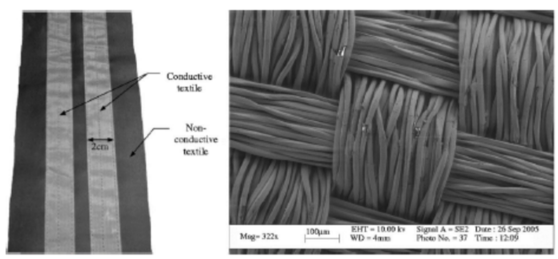


Figure 3.2: 322x Magnification of Conductive Textile, after (13).

Figure 3.3: Numerous Varieties of Conductive Textile, after (14).

Table 3.1: Selection of Metalized Fabrics From the Sample Portfolio Given by Swift Textile Metallizing, LLC.

Material Base Fiber	Metal Coating	Thickness (mm)	Electrical Resistivity (Ω/sq)
Continuous Nylon Loop	Ag	0.86	<1.5
Nylon Knit 48x21	Ag	0.18	<1.0
Nylon Tricot Knit 55x40-2	Ag	0.23	<0.5
Nylon Knit 55x40	Ag	0.18	<1.0
Nylon Knit 13x26	Ag	0.15	<5.0
Non-Woven Point Bonded 10	NiAg	0.23	<1.0
Non-Woven Point Bonded 20	NiAg	0.38	<0.1
Nylon Rip Stop	NiAg	0.10	<0.1
Nylon Rip Stop	**3NiAg**	**0.10**	**<0.05**
Nylon Heavy Rip Stop	Ag	0.18	<1.0
Nylon Teffeta	NiAg	0.13	<0.1
Spandex	Ag	0.57	<1.5

3.2 Textile Material

3.2.1 Conductive Fabric

As a first step in the development of UWB textile antennas, we characterized the electrical properties of the textile materials. As our conductive layer, we chose the triple-nickel-silver nylon rip stop from Swift Textile Metallizing. Table 3.1 shows selection of metalized fabrics from the vendor. This material has an electrical resistance less than 0.05 Ω/sq and it's only 0.12 mm thick. This textile offers the best surface conductivity of any products our vendor supplied. The materials small thickness as well as its low resistivity is ideal for the application we will be discussing in Ch: 5.

3.2.2 Dielectric

Another key component to textile antenna development is the selection of an appropriate dielectric material. This material must successfully balance all application requirements such as flexibility, durability, thickness, and dielectric loss. For example, wireless body area networks require the antenna to be lightweight, conformal, easily integrated into clothing, flexible, and inexpensive. For these applications, a lightweight, inexpensive dielectric textile is preferred. Contrasting with this would be lightweight textile antenna development for a more rugged scenario such as deployment on UAVs. UAV textile antennas must offer the same specifications as the wireless body area networks while also committing to be highly durable and tear resistant.

Durability is an important parameter when selecting textile materials. The denier rating of textiles corresponds directly to the textile strength; a higher denier rating implies higher strength. Due to its high denier rating of 1000, just shy of some Kevlar fabrics with a denier rating around 1200, as well as its relatively low loss and small thickness, the Cordura fabric was selected as a dielectric and insulating material. The cordura dielectric was tested using LCR meter at 100kHz, provided a permittivity of 2.05 and a loss tangent of 0.025. Table 3.2 shows a comparison between different dielectrics.

For all antennas presented in chapters Ch: 4 and Ch: 5 we will be using triple-nickel-silver nylon rip stop as conductive layer and cordura as dielectric. Fig. 3.4 illustrate picture of both layers. Layering the two layers yields to an antenna that is less than 1 mm in total thickness.

We verified the accuracy of our permittivity value through the development and analysis of a patch antenna operating at 2.4GHz. The return loss results are shown in Fig. 3.5.

3.3 Textile Antenna Fabrication

There are different methods for textile antenna fabrication, like screen printing, ink jet printing and using conducting textiles. The advantages of screen-printed textile antennas include: Fast and easy, Relatively inexpensive method Can also be used

Table 3.2: Selection of Dielectric Fabrics for consideration by Morris (4), Zhu (5), Moro (6), Ouyang (2) and Sankaralingam (7).

Material Base Fabric	Thickness (mm)	Relative Permittivity	Loss tangent
PDMS	4.0	Tunable to 20	<0.01
Silk	0.58	1.75	0.012
Moleskin	1.17	1.45	0.05
Felt	1.1	1.38	0.023
Fleece	2.55	1.17	0.0035
Firefighter Protective Foam	3.94	1.575	0.0238
Cordura	**0.57**	**1.90**	**0.0098**
Cotton	0.145	1.60	0.0098
100% Polyester	-	1.90	0.0045
Quartzel Fabric	-	1.67	0.0004
Jeans Cotton	2.84	1.67	-

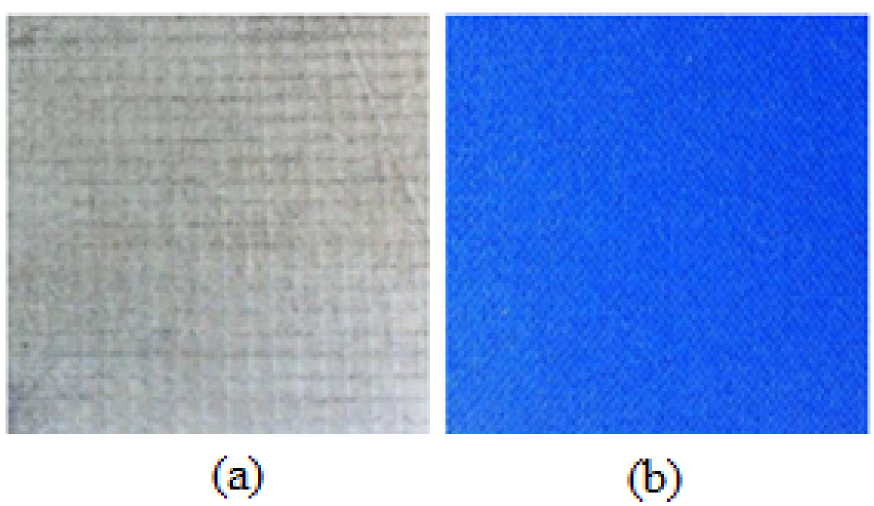


Figure 3.4: (a) Conductive layer Nilon Rip Stop 3NiAg, (b) Dielectric Layer Cordura.

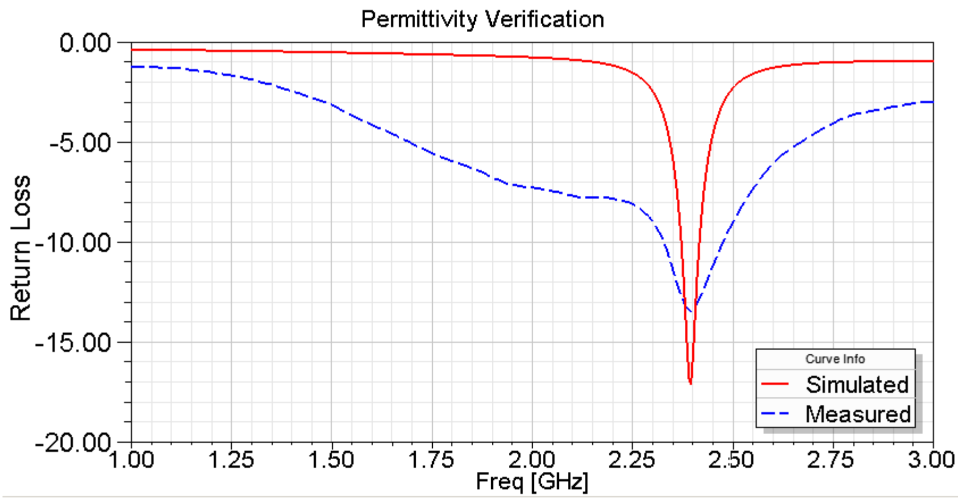


Figure 3.5: Patch Antenna Return Loss.

in mass-production. Relatively high resolution and flexible pattern are achieved on fabric. On smooth substrates, the resolution is approximately 50 m line width (industrial production). However, on uneven absorbent materials, the resolution is more limited. A minimum line resolution of 200 m can be achieved on 100 m thick polyester fabric (thickness of the film wire is 10m) has been reported in (23). However, the resolution depends on the roughness of surface: structure of the fabric, mesh of the fabric, thickness of the yarns, and so forth.

Fabrication using conducting textiles can be defined in one of the following forms:

-Use of conductive ribbons (24)

-Use of copper meshes (25)

-Embroidered using conductive thread [(24), (26)]

-Sprayed using conductive paint (24).

3.3.1 Inkjet Printing

Inkjet printing antennas can be created directly from the final design without the need for a screen and hence allows rapid production for low volumes with the flexibility for tweaking. In some cases an interface layer is used before inkjet printing using screen printing to facilitate fine resolution. Silver or copper inkjet-printed antennas have been reported in (23)

Challenges of inkjet printing include:

Challenging to inkjet print on rough or porous textiles (27) ability of the textile to withstand the ink-curing temperature maintaining a conductive track while the antenna is bent around cylindrical structures. efficiency values for inkjet-printed antennas are typically low. Adding layers is a possibility. A more comprehensive review of inkjet printing can be found in (28)
Here we present a new method that guarantee high resolution in line definition. Where patterns are laser defined, and patterns are iron-on the fabrics.

3.3.2 Precise Metalized Pattern Cutting

One of the largest concerns with the fabrication of reliable textile antennas is the ability to ensure precision in antenna dimensions. An Epilog Zing 24 Laser System was utilized to define our antenna layers to allow for high precision manufacturing. Fig. 3.6 illustrates the machine cutting precisely shape of antennas. This accuracy derives from the adjustable dot density from 100 to 1000 dpi and speed and laser power adjustable from 1 to 100. This system can accurately define microstrip line widths down to approximately 0.5 mm on this conductive fabric. We found that an 8-element microstrip fed patch array, can be accurately laser cut within five minutes at a 500dpi setting with 40% power and 25% speed. Careful consideration must be taken during the development process to ensure no dimensions call for a width less than approximately 0.5 mm. The system can also cut variety of materials: textiles, woods, glasses, and metals. The maximum allowable continuous antenna design cannot exceed 24 x 12.. The maximum material thickness cannot exceed 7.75. This fabrication process offers a quick, effective solution for cutting textile antennas. Fig. 3.7 shows the textile antennas fabricated by our group using this machine. In

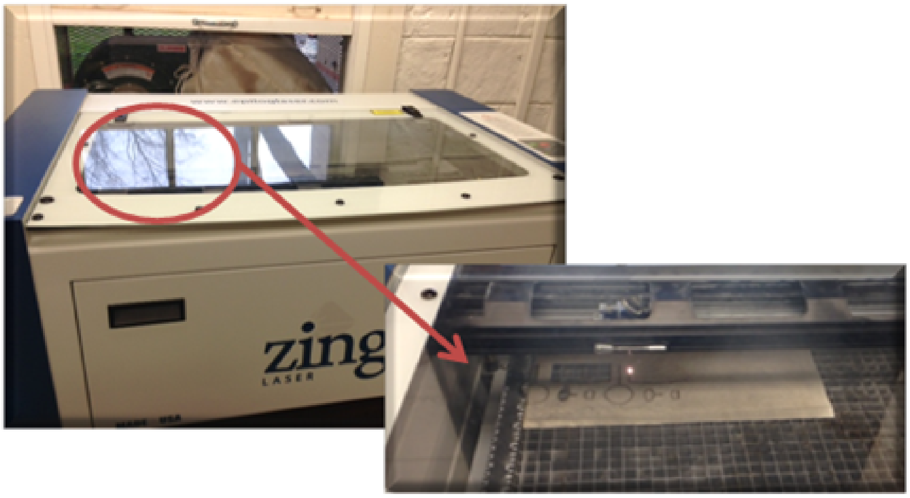


Figure 3.6: Epilog Zing 24 Laser Cutting System.

the following chapters we will talk more about some of these antennas and their application.

Process of Textile Antenna Fabrication

Wideband textile antennas have been developed with high precision. The antennas are composed of three textile layers: the top and bottom are conducting layers and are precisely defined by a laser cutting machine, while the third layer is a textile dielectric layer and sandwiched between these two conducting layers. An iron-on adhesive was used to secure multiple textile layers together. The adhesion process was fairly straightforward. After preparing the textile layers and cutting the paper-backed adhesion material to the appropriate dimensions, the adhesive layer could be laid on one of the textile layers. Applying heat causes the glue to bond with the textile layer and allows for removal of the original paper backing. Then the second textile layer is aligned with the first layer in the desired location. Applying heat to this second layer, once it is in position, bonds the two textile layers to one another. A diagram of this process is presented in Fig. 3.8. The bonding is strong and durable

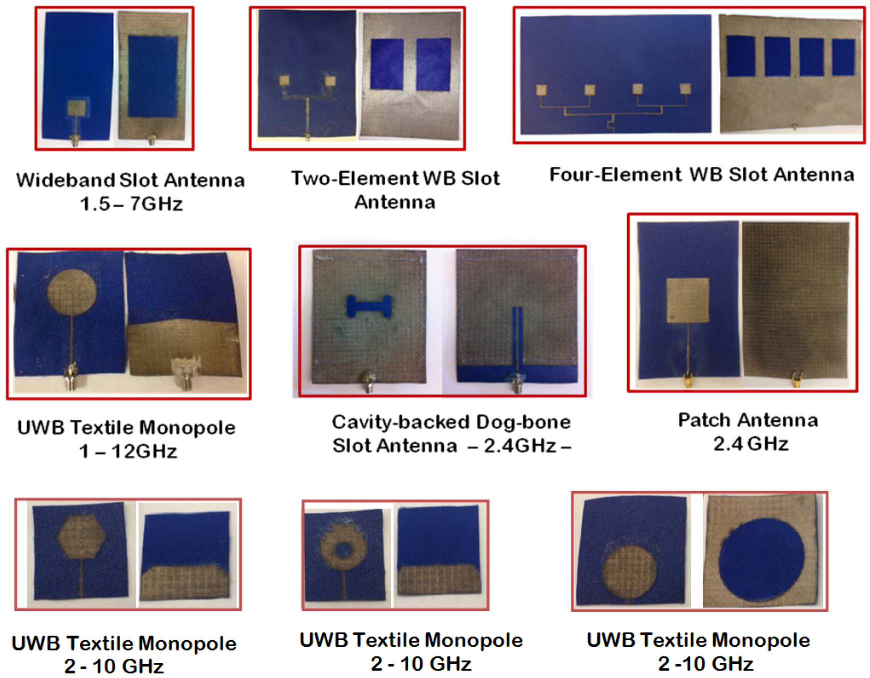


Figure 3.7: Conductive Textile Antennas Fabricated Using Epilog Zing 24 Laser Cutting.

even permitting machine washing without losing its adhesiveness. This ensures no air gaps exist between the conductor and dielectric layers of the antenna.

Once the multiple layers have been secured together, the various designs can be electrically connected to external equipment. This connection has been achieved in this thesis through the use of a two-part conductive epoxy, shown in Fig. 3.9. The selected epoxy was AI Technologys EG8028 High Strength Two Component Electrically Conductive Epoxy Paste Adhesive. An SMA connector was used for antenna testing and applied using this two-part conductive epoxy glue. This connection can be left to dry and secured using hot glue if added durability is desired. An additional solution to the electrically connecting multiple layers is by using conductive thread shown in Fig. 3.10. Though resistive in large lengths, ¡100 Ω/cm, this thread can be overlapped and used over short distances very effectively. We also have the ability to sew vias into the designs through the use of conductive thread (Fig. 3.11). These vias can be extrapolated to function as substrate integrated waveguides

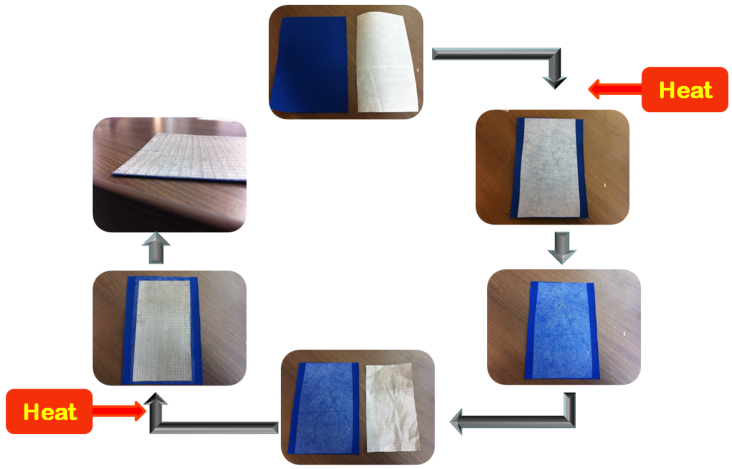


Figure 3.8: Bonding the Metalized Patterns to Substrates.

Figure 3.9: Two-Part Conductive Epoxy.

Figure 3.10: Electrically Conductive Thread.

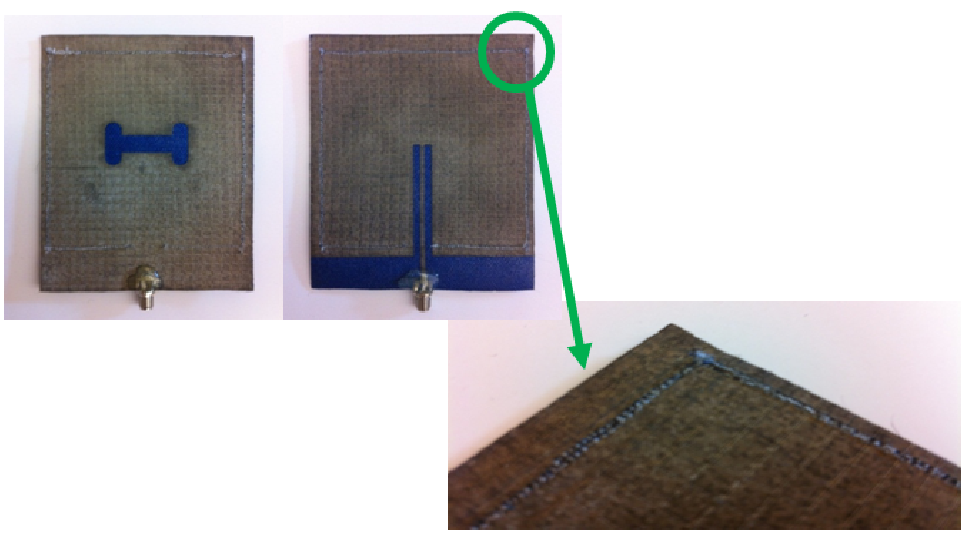


Figure 3.11: Cavity-backed Dog-bone Slot Antenna 2.4GHz.

3.3.3 Conclusion

Four Different techniques of metallization (vacuum deposition, ion plating, electroplating, and electroless plating) were presented in this chapter. Also in this chapter we presented a selection of metalized fabrics and dielectrics. Triple-nickel-silver nylon rip stop (conductive layer) and cordura (dielectric) were chosen to build all the textile antennas fabricated and presented by the author. We have investigated the performance of a laser defined antenna then iron-on a low loss fabric. The print quality is important and line definition is essential especially in these very narrow line traces. The printed antenna is flexible and has an even surface, definitely some reliability testing is still required including laundry treatments and in normal field use.

Chapter 4

Wideband Textile Slot Antenna Array

4.1 Abstract

In this chapter, we present the design process of a single element slot antenna for use in wearable applications. This antenna is further developed into a two-element and four-element antenna arrays. The high-precision laser cutting machine allows us to achieve relatively higher tolerances and accuracy greater than that achieved by cutting through manual means. The developed antennas offer flexible, light-weight and bendable properties. The antennas can be easily incorporated into clothing using a simple iron-on adhesive process, section 3.3. Additionally iron-on process allows for the fabric to be washed without losing its adhesion.

4.2 Single Element Slot Antenna Design

Using the properties for each textile layer, a slot antenna is designed which operates with bandwidth of 4.28:1. We feed this antenna with a microstrip and a shaped feed similar to the slot opening as described by (29). This antenna was designed using

Ansofts HFSS and is shown in Fig. 4.1. The return loss and radiation patterns for this antenna are presented in Fig. 4.2 and Fig. 4.3 at discrete frequencies of 2 GHz and 5 GHz. Results agree well with simulation across the operating range.

4.3 Two Element Textile Slot Antenna

After validating the slot antenna as a single element, a two-element array was developed. A picture of this antenna is shown in Fig. 4.4. The return loss of the

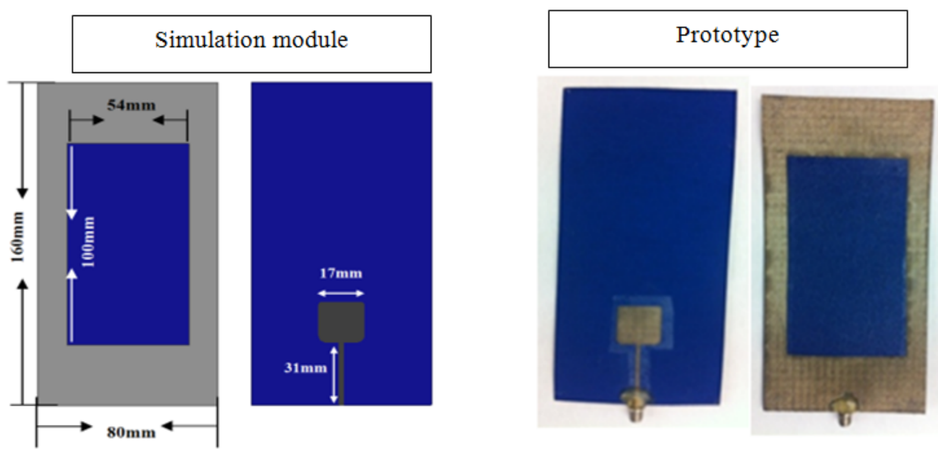


Figure 4.1: Wideband Slot Antenna Dimensions.

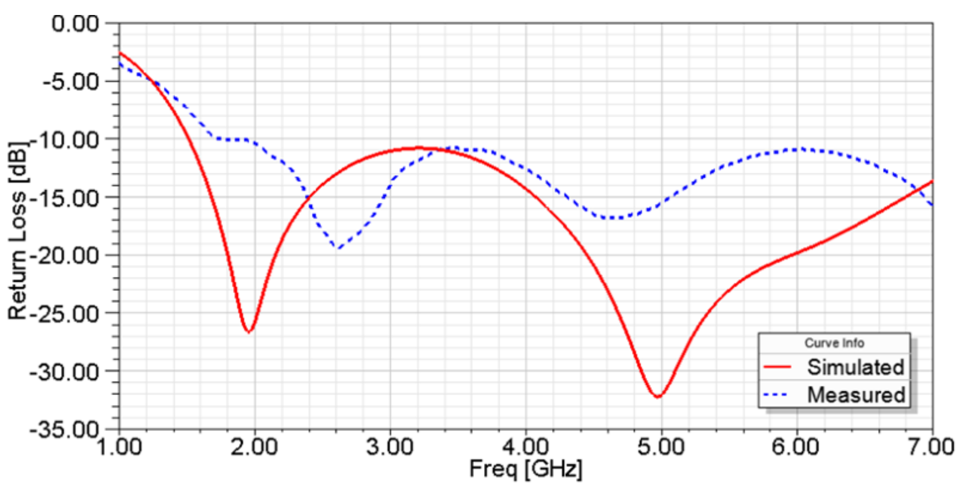


Figure 4.2: Single Element Slot Antenna Return Loss.

two-element array shows good agreement with simulation. This is depicted in Fig. 4.5.

The radiation patterns of the two-element array can be seen in Fig. 4.6. The maximum gain across the frequency band can be seen in Fig. 4.7.

4.4 Four Element Textile Slot Antenna

Four element array was built as well. A picture of the top and bottom of the four element array are presented in Fig. 4.8 and Fig. 4.9 The return loss of the 4-element array and the radiation pattern are shown in Fig. 4.10 and Fig. 4.12

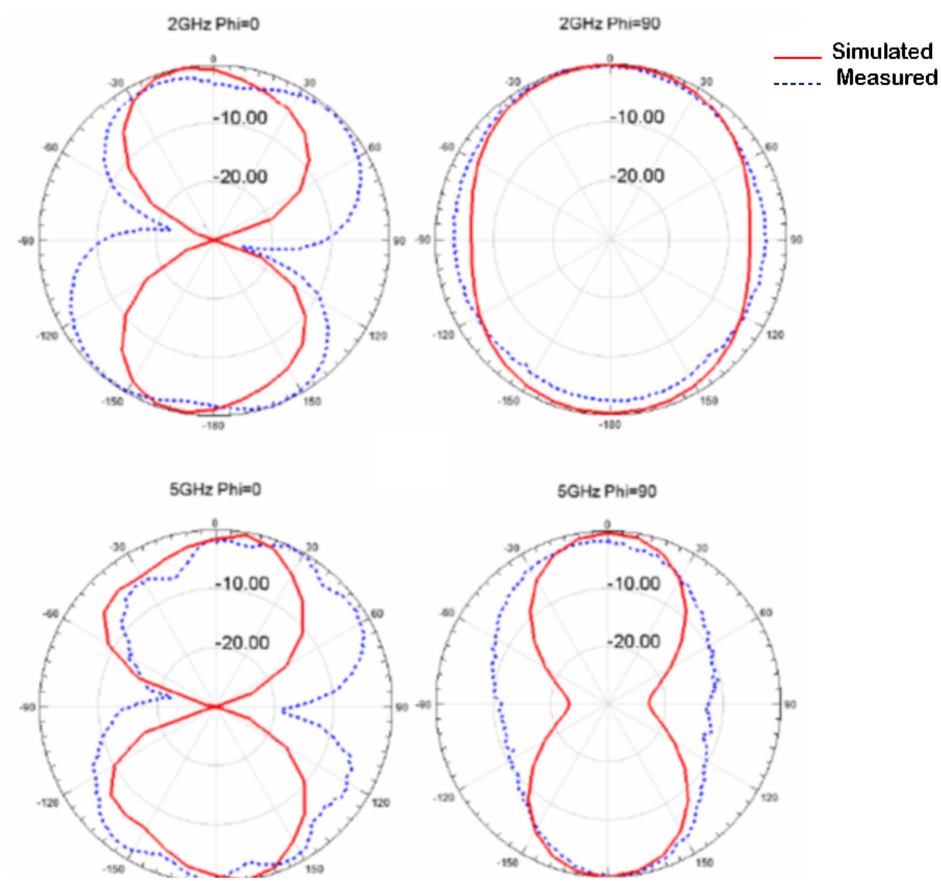


Figure 4.3: Radiation Patterns at 2 GHz and 5 GHz.

The 4-element array was built using the same exact method described earlier. Using the laser cuter, it takes between 5 to 10 min to cut the top and bottom layer of the antenna.

Testing the 4-element array was quite challenging because of the size of the antenna. It was hard to keep the antenna flat and perpendicular to the surface. A foam frame was built to support the antenna inside the anechoic chamber. We believe that the

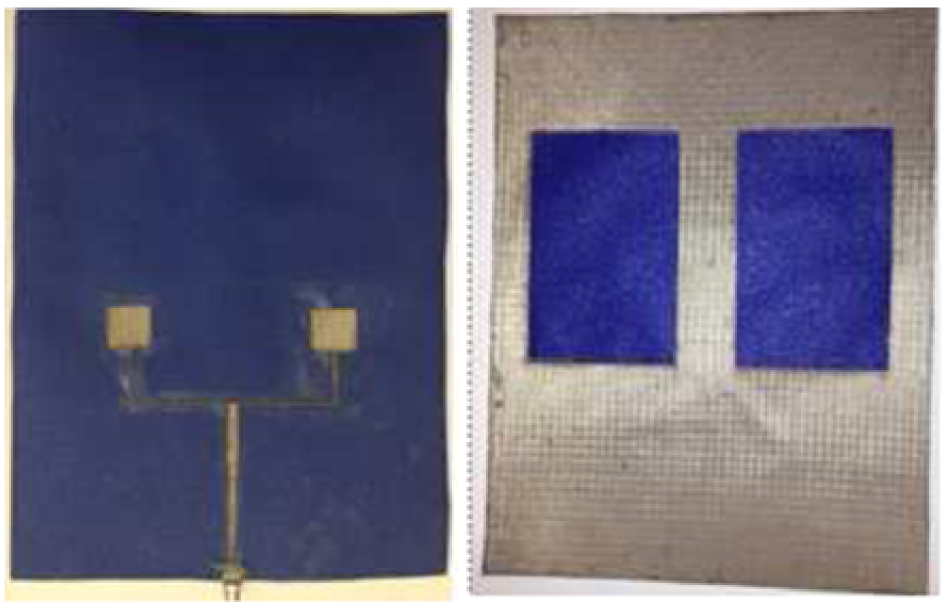


Figure 4.4: Wideband Two-Element Slot Antenna.

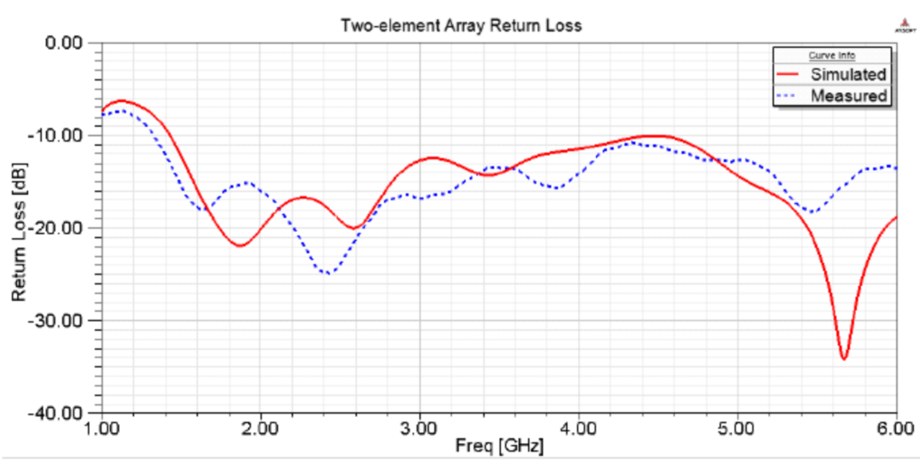


Figure 4.5: Return Loss of the Two-Element Slot Array.

frame did not affect the result because of the permittivity of the foam almost similar to the permittivity of air. Fig. 4.11 shows how the 4-element array was supported during the radiation pattern measurements.

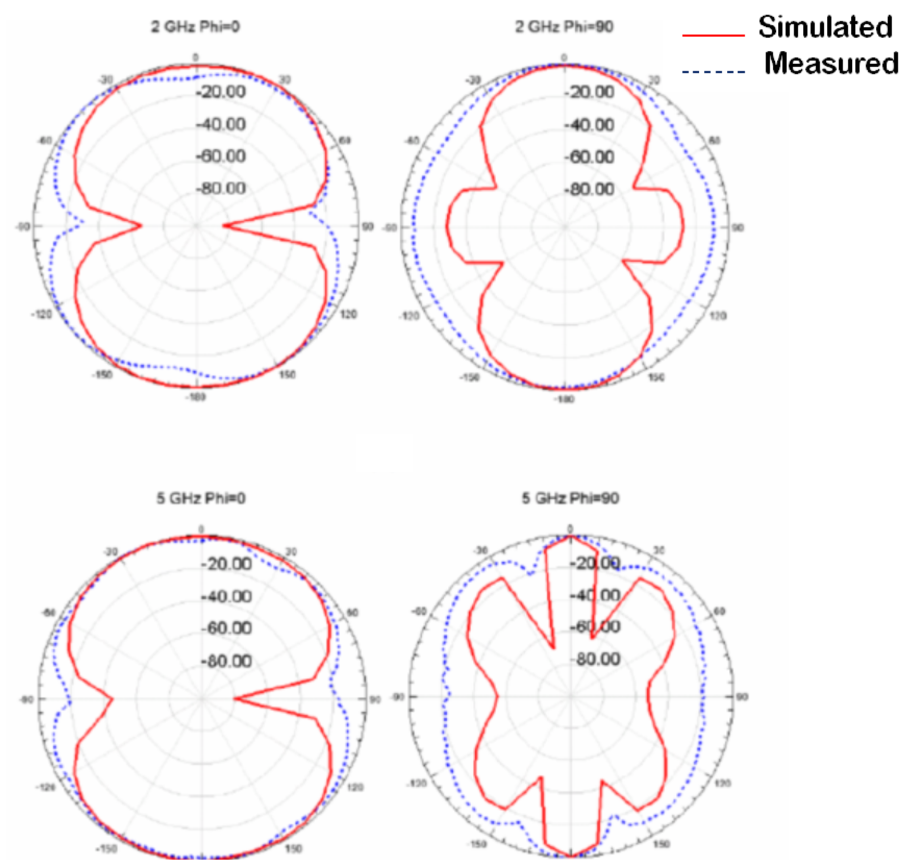


Figure 4.6: Radiation Patterns for the 2-Element Array at 2 GHz and 5 GHz.

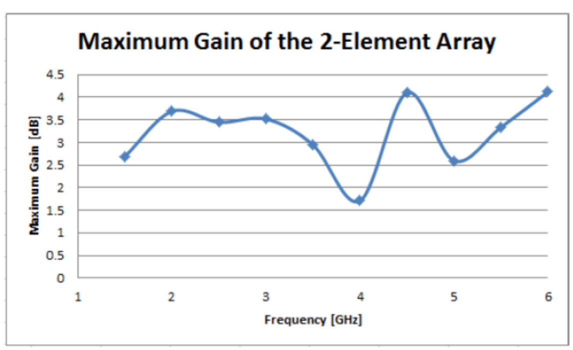


Figure 4.7: Maximum Gain of 2-Element Array.

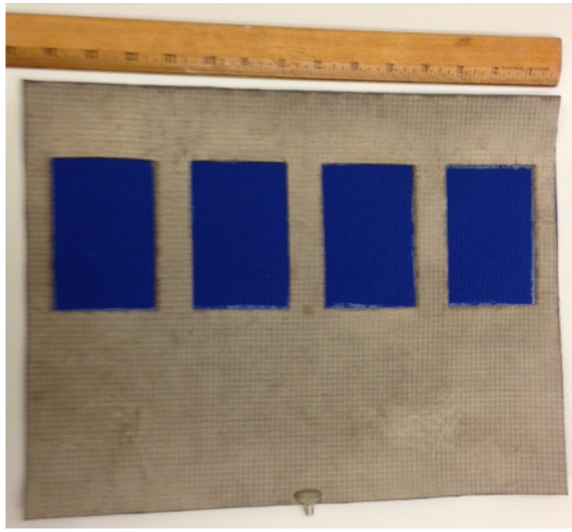


Figure 4.8: 4-Element Slot Array Bottom View.

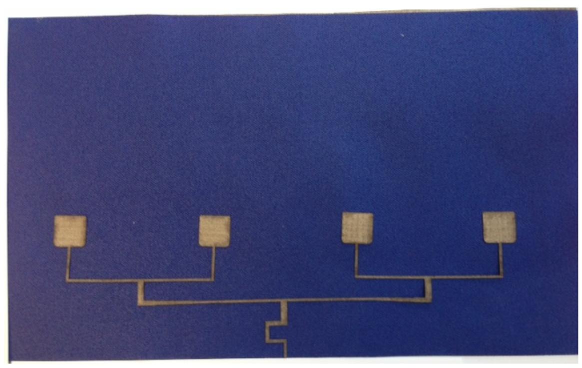


Figure 4.9: 4-Element Slot Array Top View.

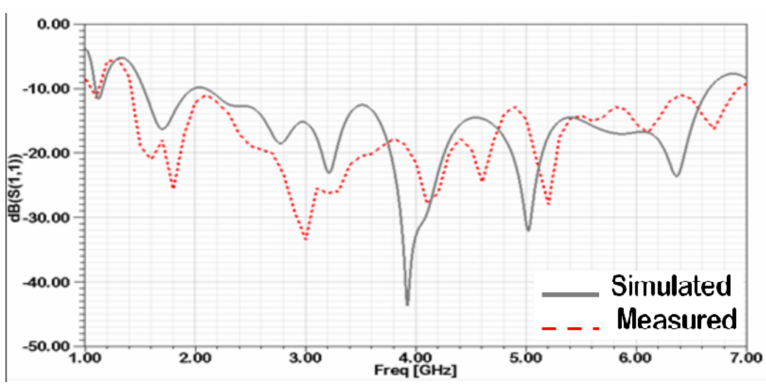


Figure 4.10: 4-Element Array Slot Antenna Return Loss.

4.4.1 Conclusion

After the development and validation of a single-element slot antenna, a two and four element array textile slot antennas have been developed using the lazer cuter to demonstrate the fabrication capability for relatively bigger textile antennas. Difficulty was encountered in the fabrication and testing process of these antennas. The spacing and straightness of the feed lines are important parameters for the antenna design. Discrepancies existing between simulation and measurement are likely a result of these inaccuracies.

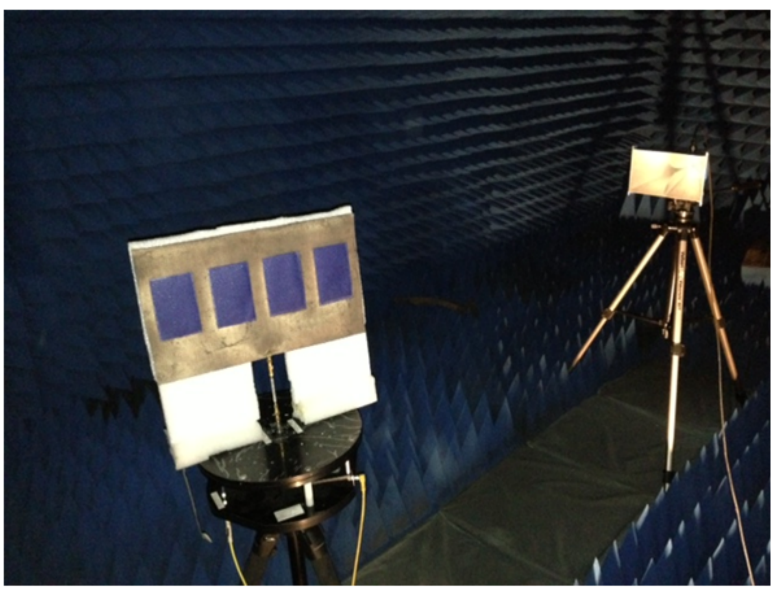


Figure 4.11: 4-Element Array Slot Implemented on a Foam Frame Inside the Anechoic Chamber.

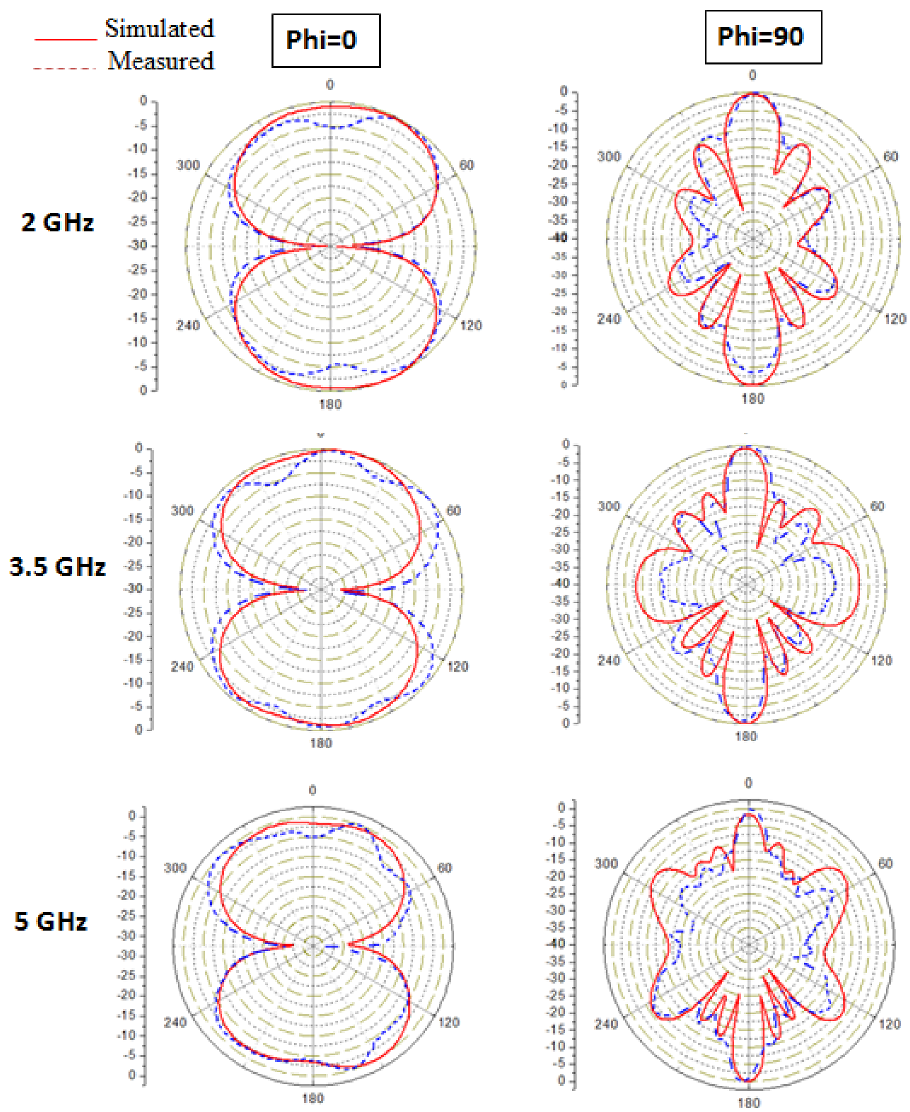


Figure 4.12: 4-Element Array Slot Antenna Radiation Pattern.

Chapter 5

Wideband Monopole Textile Antenna Development for UWB Localization

5.1 Abstract

Tags integrated into clothing enable monitoring of people for different reasons and even without their conscious effort. In these cases, it requires tags to be an unnoticeable part of clothing and comfortable to wear, reliable, and tested with moisture and laundry tests. The potential and possibilities of wearable healthcare and monitoring systems is steadily increasing. It is possible with fabric antennas/systems to hide the technology that often frightens patients, while discreetly providing assistance. Cases like involuntary treatment and dementia care might require unnoticeable monitoring as some patients may seek to remove suspicious devices.

In health care, it is becoming essential to monitor, track, and identify patients remotely. These sensors can be used to carry out many tasks like body temperature, sleep apnea, body limb movement, and even monitor prescribed exercises in rehabilitation process.

In this chapter, we discuss in detail one of these tag applications that can be used for monitoring and tracking persons. In this system, a monopole textile antenna has been developed using an Epilog Zing 24 Laser System Ch: 3. This antenna design offers conformal, bendable, and washable properties. These UWB textile antennas can be applied to localization systems and can provide accurate estimation of wearers location. Accurate localization is achieved using these antennas and a UWB localization system. As the authors show in (10), UWB antennas can be fabricated on thin layers of dielectric fabric, with thickness around 0.5 mm, to allow for easy integration into wearable applications.

5.2 Monopole Design

There have been many papers written on the design of wideband antennas constructed from fabrics Ch: 2. We follow these approaches and those taken in (30) to develop a wideband textile monopole antenna to use in localization applications.The monopole textile antenna was designed using HFSS, where the design goals are: 0.5dB gain, from 1 to 15GHz bandwidth and less than 1 mm thickness. Fig. 5.1 below illustrates the design and the sizing parameters associated with the antenna. The entire antenna is realized on a fabric square 60 mm x 70 mm in size.
Using the laser precision cutting machine and the iron-on adhesive discussed in Ch: 3, we fabricated this design as shown in Fig. 5.2. This antenna, due to its fabric composition and small size, can be easily integrated into clothing.
The measured return loss for this antenna provides acceptable bandwidth for use in our localization experiment. The current localization system functions at a frequency range of 5-9GHz. As you can see in Fig. 5.3, this monopole design has acceptable return loss over the range of 2-11GHz. Fig. 5.4 compares the radiation patterns of the monopole antenna at 3, 6, and 9GHz.

Parameter	Size (mm)
L (mm)	70
W (mm)	60
Lms (mm)	32
Lg (mm)	28
R (mm)	14

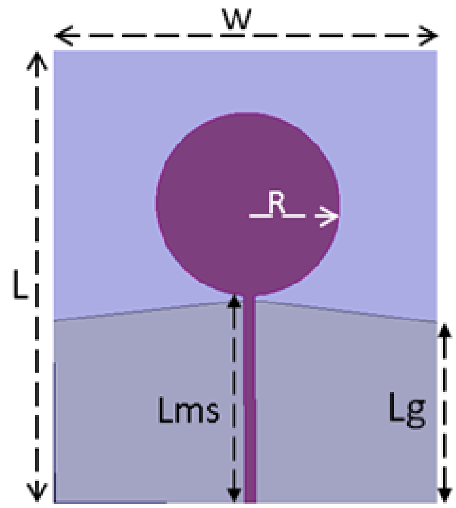


Figure 5.1: UWB Monopole Design.

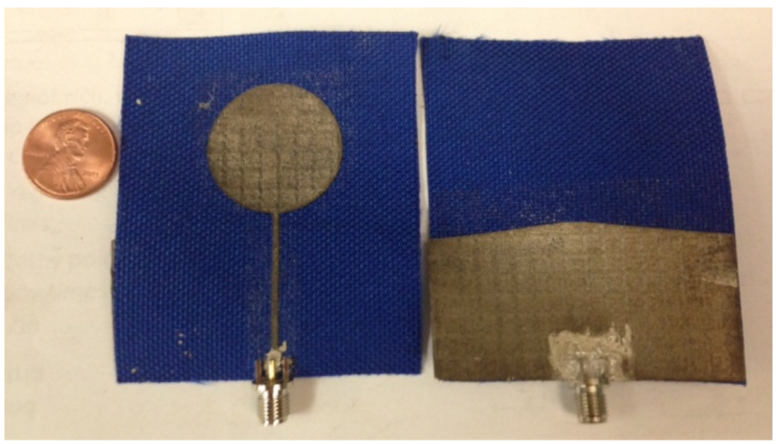


Figure 5.2: Fabricated UWB Monopole.

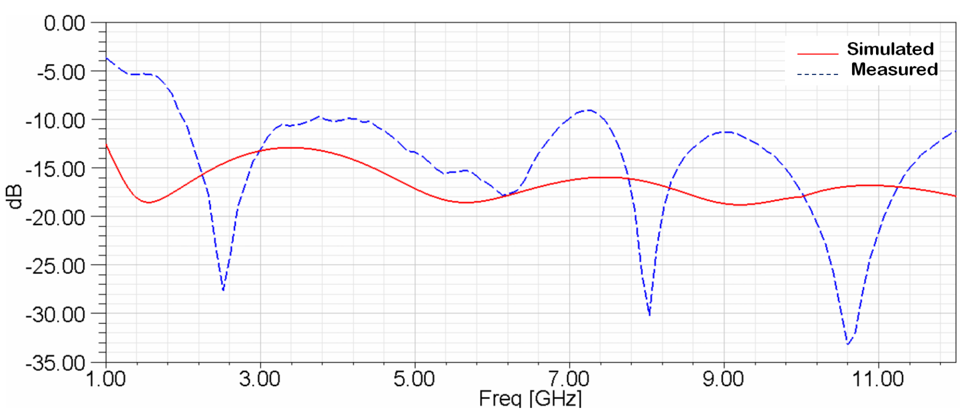


Figure 5.3: Simulated and Measured Monopole Return Loss

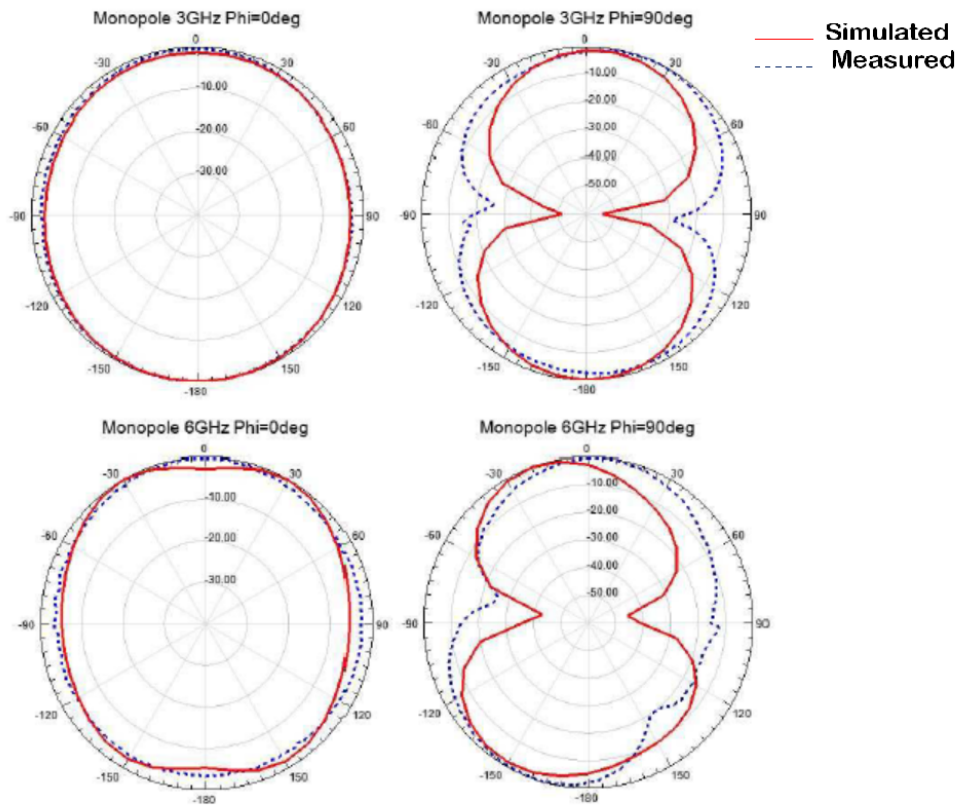


Figure 5.4: Simulated and Measured Monopole Return Loss

5.3 Monopole Localization

After fabricating and testing the functionality of our monopole design, we applied the antenna to an indoor localization system using our fabric antenna as a part of a tag. Fig. 5.5

We desired to test the potential of textile antennas as a new technique for human movement tracking. The localization system uses a tag that transmits a UWB pulse with FWHA of 300ps and modulated at a center frequency of 8GHz. The pulse is received by N base stations and uses the difference in time of arrival to triangulate the tag position. Using Four vivaldi antennas, we can track the tag in 3 dimensions; using more base stations improves S/N ratio and provides redundancy. We use a leading edge algorithm to pin out the pulse time. The measurements are verified utilizing an optical tracking system which has an accuracy of 0.3 mm.

We looked first to the reliability of the fabric monopole in producing the pulse compared to the original copper monopole printed on RT/Duroid substrate usually used by the system. Fig. 5.6 shows three received and down converted pulses: that of the original tag antenna, the fabric monopole, and the fabric monopole placed near the body. Definitely, there are few challenges like: effect of fabric on pulse shape, effect of losses on amplitude, impact of body on performance and effect of both on leading edge.

We can see the pulses are similar as they have approximately the same width Fig. 5.6. However, the pulse produced by the fabric antenna in space is relatively lower. This amplitude drop is expected due to the high loss of the cordura and the moderate conductivity of the conductive fabric. The figure also shows how the pulse is affected when placed against the body. The pulse shape remains similar and has higher amplitude as a result of the constructive interference from the back reflection of the body. The pulses leading edge, a critical parameter for the localization leading edge algorithm, is acceptable for all three cases.

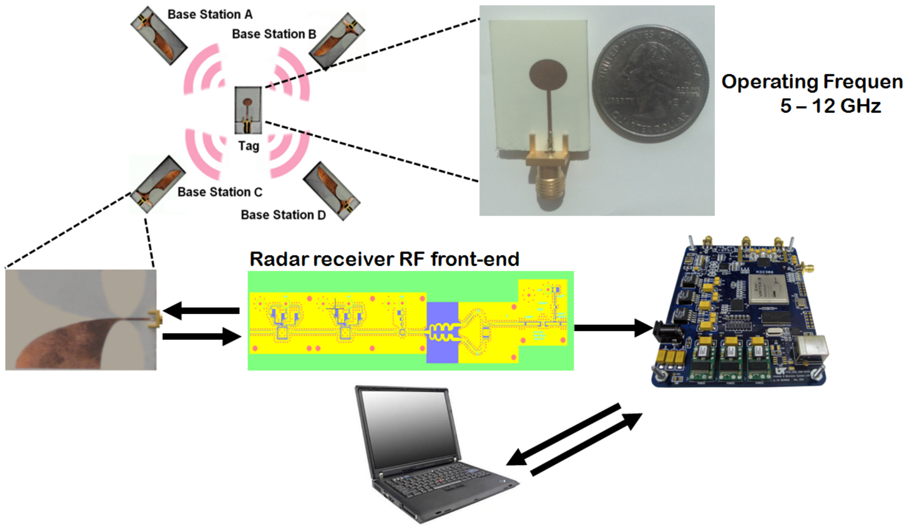


Figure 5.5: UWB Localization System

We track the tag using two base stations for 1D localization. The tag uses the fabric monopole as the transmitting antenna. An optical probe is also attached to the tag so we can use it as a reference for comparing the two tracking positions. Calibration was performed to account for the offset distance between the fabric antenna and the optical probe. Our experiment performed real-time tracking. During this experiment we compared our fabric monopole to an optical sensing system.

If we let the distance from the transmitting tag to base station 1 be A and the similar distance to base station 2 be B, Fig. Fig. 5.7 shows the difference in distance, B-A, versus the time difference of arrival of base stations A and B. The figure shows a total agreement of the UWB and optical probe with error less than few centimeters. This error becomes more visible as the distance from the base stations increases beyond five feet. This can be attributed to a diminishing signal to noise ratio with increasing distance. Further techniques can be applied to further increase this range.

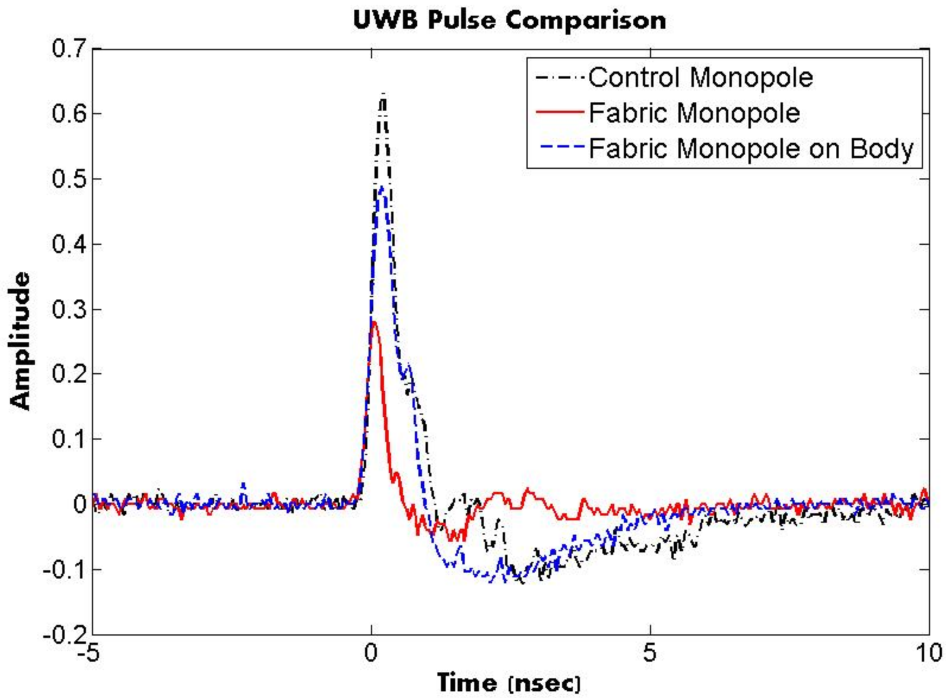


Figure 5.6: UWB Pulse Comparison

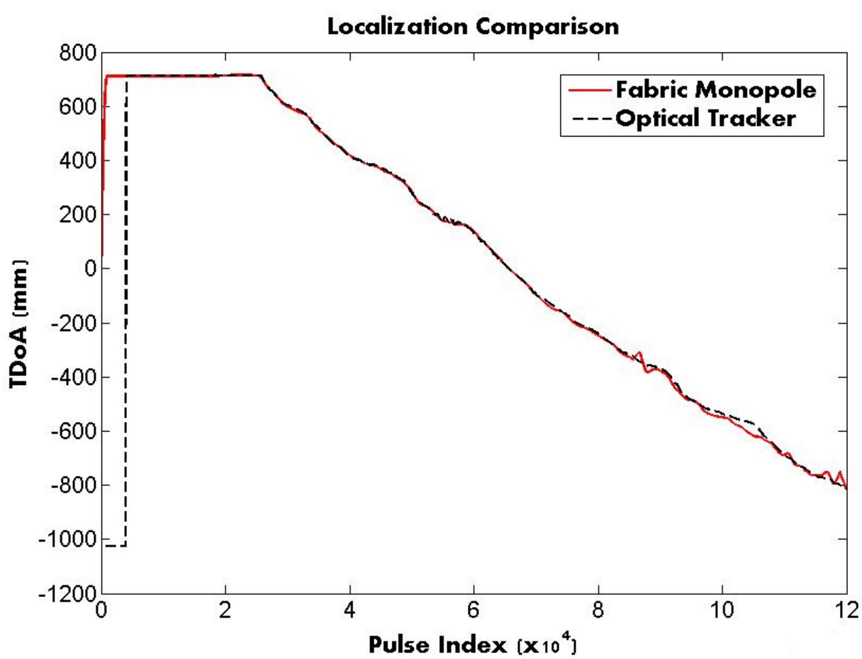


Figure 5.7: Comparison of Optical Tracker Localization and Fabric Monopole Localization

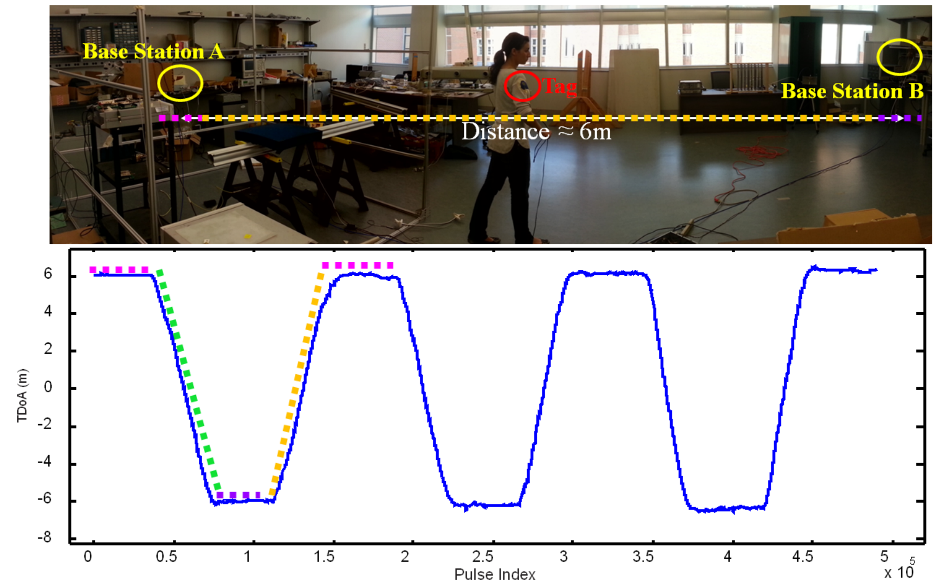


Figure 5.8: Tracking Person Using UWB Indoor Localization System

5.4 UWB Indoor Localization Experiment

A second experiment was performed over a larger range. The two antennas were placed about six meters away. The antenna was attached to the clothes of a walking person at the shoulder place. The person moves in a straight line from antenna A to antenna B on the straight line connecting the two antennas. The moving person walks from antenna A to antenna B and waits for a short period and then back to antenna A again. The movement is repeated couple of times.

Fig. 5.8 shows the TDoA i.e. the time of arrival of pulse at antenna B minus the time of arrival of pulse at antenna A. The time of arrival is converted to meters by multiplying by the speed of light. The TDoA shows +6 m when the moving person is closest to antenna A and -6 meters when the moving person is closest to antenna B.

It is imperative to recognize in this test setup that the instrument we use for ground truth comparison i.e. optical tracker has a limited view. The optical tracker should cover the two receiving, base-station, antennas and the moving tag for a successful usage as ground truth instrument and that was impossible to do with antennas separated with six meters.

5.4.1 Conclusion

Textile UWB monopole antenna has been developed for use in localization systems. These antennas are precisely fabricated using a laser cutter and offer dimensional qualities which allow for easy integration into garments and other clothing accessories. Tolerances approaching 0.5 mm are far more accurate than one could hope to achieve through manual cutting. Flexibility and durability of the antenna also promote the use of this technique for use in body area network and ultra-wideband applications. With proper precautions, this technology could be expanded and usefully applied to locate victims in the wake of a natural disaster.

Chapter 6

Conclusion

There is a trend to further exploit the potential use of universal garments by integrating more functionality beyond the main purpose of clothing which is protecting the human body against environmental conditions. Additionally, a new generation of materials is available has led to the concept of wearable intelligent textile systems. It is intention to equip firefighters, paramedics and other rescue workers with the most advanced materials and to additionally monitoring their vital signs will be enabled in the next generation of professional protective clothing. These garments can be used in a variety of applications like monitoring the wearers vital signs, location, activity and capable of observing environmental conditions, in a comfortable and unobtrusive way. Such huge amount of data obtained by these sensors, would require wireless communication tools for efficient data transfer. Wireless communication infrastructure allows transmitting substantial amount of data to a supporting base station.

Adding the textile wireless system to the fabric, should not affect its flexibility and comfort, and the antennas should be fully integrable into the garments. Generally, however, there are two options either using electrotextiles that would allow manufacturing of these antennas entirely out of textile materials, or developing a simple printing scheme on the textile that would provide precise definition of highly conductive layers on the fabrics, or even embedded in its layers. A lead application area for these wearable textile systems is undoubtedly protective clothing for work wear such as fire fighter garments.

This thesis introduces a precise textile antenna fabrication methodology using low cost, highly precise definition scheme using laser defined metallization patterns that could be easily ironed on. The presented method in Ch: 3 of this thesis has been used to develop variety of high performance antennas on Cordura fabric material including a location aware antennas for possible integration in a fire fighter outer garment. This multilayer monopole antenna is designed for operation in the UWB range for short range communication to transmit the fire fighters location and eventually life signs to a nearby base station. The monopole antenna was previously fabricated with 0.5mm tolerance and integrated into the garment, the antenna requires a finite ground plane and operates in the presence of the body, a condition which may result in changing antenna characteristics. The proposed antenna provides enough robustness to preserve its characteristics under these circumstances. This research paves the way for a new generation of fire fighter garments. Flexibility and durability of the antenna also promote the use of this technique for use in body area network and ultra-wideband applications. With proper precautions, this technology could be expanded and usefully applied to locate victims in the wake of a natural disaster.

In designing a textile antenna there many issues that need to be considered. In general, there are main issues that need to be addressed in the design of these textile antennas:; including Elastic properties of textile materials: where the variation of dimensions due to stretching and compression are typical for fabrics. This dimensions changes could lead to changes in the resonant length of the antenna and detune its frequency band while the substrate thickness changes the resonant frequency as well as the input impedance bandwidth. So, it is desirable to avoid elastic fibers. Also, If the fabric absorbs water, then its dielectric constant will change dramatically, as the dielectric constant of water is much higher. When a fabric antenna absorbs water, the moisture changes the antenna performance parameters dramatically and it will reduce its resonant frequency. Fabric antennas can absorb sweats or rain if placed on top of jackets. Hence, some sort of buffer layers can be used to eliminate such effect. Additionally, wearable antennas cannot be placed on flat surfaces especially in places like sleeves where bending is expected to occur. Bending could affect the resonance length of antennas; especially if it is a narrow band antenna. Moreover, antennas performance will change significantly when placed next to the human body. In addition, they should be tested for their radiation levels. They should be designed taking the effect of human body, limited ground plane into account. In addition, special attention must be paid to the Specific Absorption Rates (SAR), which aids in the quantitative study of power absorption issues required to meet the standards in order to avoid harm to human body. Thus, in the vicinity of the human body, several issues should be considered such as antenna input-match performance, radiation characteristics of the antenna, and the power absorbed in the human body. Lastly, If the body is moving too, it will have an impact on the antenna characteristics and should be accounted for as signals will be affected from local scattering. Human body is subject to many small movements even when standing, sitting, during normal activities, and even during playing of sports.

There are different methods for textile antenna fabrication, like screen printing, ink jet printing and using conducting textiles. The advantages of screen-printed textile antennas include: Fast and easy, relatively inexpensive method, Can also be used in mass-production, and relatively high resolution and flexible pattern are achieved on fabric. On smooth substrates, the resolution is approximately 50m line width (industrial production). However, on uneven absorbent materials, the resolution is more limited. A minimum line resolution of 200m can be achieved on 100m thick polyester fabric (thickness of the film wire is 10m) has been reported. However, the resolution depends on the roughness of the surface: structure of the fabric, mesh of the fabric, thickness of the yarns, and so forth. Inkjet printing antennas, is a new technology, and can be created directly from the final design without the need for a screen and hence allows rapid production for low volumes with the flexibility for tweaking. In some cases an interface layer is used before inkjet printing using screen printing to facilitate fine resolution. Silver or copper inkjet-printed antennas have been reported. But, it has it challenges that include difficultly to inkjet print on rough or porous textiles, ability of the textile to withstand the ink-curing temperature maintaining a conductive track while the antenna is bent around cylindrical structures, and efficiency values for inkjet-printed antennas are typically low.

Many techniques have been developed to define the textile antennas but they are mostly manual and typically result in inaccuracies in the fabrication process. Here we present a new method that guarantee high resolution in line definition. Where patterns are laser defined, and patterns are iron-on the fabrics. The method can provide high precision of up to 0.5 mm accuracy, but after the development and validation of single-element and large array antennas, we see still remaining fabrication challenges. Difficulty was encountered in the fabrication and testing process of these antennas. The spacing and straightness of the feed lines are important parameters for the antenna design. Discrepancies existing between simulation and measurement are likely a result of these inaccuracies.

Bibliography

[1] H. Giddens, D. Paul, G. Hilton, and J. McGeehan, "Influence of body proximity on the efficiency of a wearable textile patch antenna," in *Antennas and Propagation (EUCAP), 2012 6th European Conference on*. IEEE, 2012, pp. 1353–1357. vii, 9, 11

[2] Y. Ouyang and W. J. Chappell, "High frequency properties of electro-textiles for wearable antenna applications," *Antennas and Propagation, IEEE Transactions on*, vol. 56, no. 2, pp. 381–389, 2008. vii, viii, 13, 14, 15, 27, 33

[3] M. A. R. Osman, M. K. Abd Rahim, M. Azfar Abdullah, N. A. Samsuri, F. Zubir, and K. Kamardin, "Design, implementation and performance of ultra-wideband textile antenna," *Progress In Electromagnetics Research B*, vol. 27, pp. 307–325, 2011. vii, ix, 19, 21, 22, 23, 27

[4] S. E. Morris, Y. Bayram, L. Zhang, Z. Wang, M. Shtein, and J. L. Volakis, "High-strength, metalized fibers for conformal load bearing antenna applications," *Antennas and Propagation, IEEE Transactions on*, vol. 59, no. 9, pp. 3458–3462, 2011. vii, viii, 5, 6, 8, 27, 33

[5] S. Zhu and R. Langley, "Dual-band wearable textile antenna on an ebg substrate," *Antennas and Propagation, IEEE Transactions on*, vol. 57, no. 4, pp. 926–935, 2009. vii, 9, 33

[6] R. Moro, S. Agneessens, H. Rogier, and M. Bozzi, "Wearable textile antenna in substrate integrated waveguide technology," *Electronics letters*, vol. 48, no. 16, pp. 985–987, 2012. vii, viii, 10, 11, 27, 33

[7] S. Sankaralingam and B. Gupta, "Determination of dielectric constant of fabric materials and their use as substrates for design and development of antennas for wearable applications," *Instrumentation and Measurement, IEEE Transactions on*, vol. 59, no. 12, pp. 3122–3130, 2010. vii, 33

[8] Z. Wang, L. Zhang, Y. Bayram, and J. L. Volakis, "Embroidered e-fiber-polymer composites for conformal and load bearing antennas," in *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*. IEEE, 2010, pp. 1–4. viii, 7, 9, 27

[9] 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*, vol. 1. IEEE, 2005, pp. 466–469. viii, 15, 16, 17, 27

[10] M. Klemm and G. Troester, "Textile uwb antennas for wireless body area networks," *Antennas and Propagation, IEEE Transactions on*, vol. 54, no. 11, pp. 3192–3197, 2006. viii, 1, 7, 8, 9, 10, 18, 19, 20, 27, 50

[11] J. G. Santas, A. Alomainy, and Y. Hao, "Textile antennas for on-body communications: Techniques and properties," in *Antennas and Propagation, 2007. EuCAP 2007. The Second European Conference on*. IET, 2007, pp. 1–4. ix, 23, 24, 25, 27

[12] C. Pickett, M. Barham, T. Gafford, D. Hutchinson, J. Jordan, L. Maxey, B. Moran, J. Muhs, R. Nodine, and M. Simpson, "A continuous automated vault inventory system (cavis) for accountability monitoring of stored nuclear materials," *Oak Ridge Y-12 Plant Report (available through OSTI), Y/DW-1351*, 1994. ix, 30

[13] M. Chedid, I. Belov, and P. Leisner, "Experimental analysis and modelling of textile transmission line for wearable applications," *International Journal of Clothing Science and Technology*, vol. 19, no. 1, pp. 59–71, 2007. ix, 30

[14] H. to Get What You Want, http://www.kobakant.at/DIY/?p=376, March 2013. ix, 30

[15] H. Horie and H. Iwasaki, "Wearable finger ring type antenna made of fabric cloth for ban use at uhf and ism bands," in *Microwave Workshop Series on RF and*

Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO), 2013 IEEE MTT-S International. IEEE, 2013, pp. 1–3. 4

[16] A. Galehdar and D. V. Thiel, "Flexible, light-weight antenna at 2.4 ghz for athlete clothing," in *Antennas and Propagation Society International Symposium, 2007 IEEE.* IEEE, 2007, pp. 4160–4163. 4

[17] M. Komeya and H. Shimasaki, "Studies on a cavity-backed slot antenna made of a conductive textile bent along a spherical surface," in *Electromagnetic Theory (EMTS), Proceedings of 2013 URSI International Symposium on.* IEEE, 2013, pp. 561–564. 5

[18] H. Shimasaki and M. Tanaka, "Measurement of the roundly bending characteristics of a cavity-backed slot antenna made of a conductive textile," in *Microwave Conference Proceedings (APMC), 2011 Asia-Pacific.* IEEE, 2011, pp. 1598–1601. 5, 27

[19] W. Thompson, R. Cepeda, G. Hilton, M. A. Beach, and S. Armour, "An improved antenna mounting for ultra-wideband on-body communications and channel characterization," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 59, no. 4, pp. 1102–1108, 2011. 9, 10

[20] G. Q. Luo, Z. F. Hu, L. X. Dong, and L. L. Sun, "Planar slot antenna backed by substrate integrated waveguide cavity," *Antennas and Wireless Propagation Letters, IEEE*, vol. 7, pp. 236–239, 2008. 10

[21] swicofil, http://www.swicofil.com/textile_metallization.html, January 2013. 29

[22] B. K. Little, Y. Li, V. Cammarata, R. Broughton, and G. Mills, "Metallization of kevlar fibers with gold," *ACS applied materials & interfaces*, vol. 3, no. 6, pp. 1965–1973, 2011. 29

[23] Y. Kim, H. Kim, and H.-J. Yoo, "Electrical characterization of screen-printed circuits on the fabric," *Advanced Packaging, IEEE Transactions on*, vol. 33, no. 1, pp. 196–205, 2010. 34, 35

[24] J. Matthews and G. Pettitt, "Development of flexible, wearable antennas," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on.* IEEE, 2009, pp. 273–277. 34

[25] T. Maleszka, M. Preisner, and P. Kabacik, "Meshed ground plane structures for textile antennas," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on.* IEEE, 2009, pp. 713–717. 34

[26] J.-S. Roh, Y.-S. Chi, J.-H. Lee, Y. Tak, S. Nam, and T. J. Kang, "Embroidered wearable multiresonant folded dipole antenna for fm reception," *Antennas and Wireless Propagation Letters, IEEE*, vol. 9, pp. 803–806, 2010. 34

[27] V. Sanchez-Romaguera, M. A. Ziai, D. Oyeka, S. Barbosa, J. S. Wheeler, J. C. Batchelor, E. A. Parker, and S. G. Yeates, "Towards inkjet-printed low cost passive uhf rfid skin mounted tattoo paper tags based on silver nanoparticle inks," *Journal of Materials Chemistry C*, vol. 1, no. 39, pp. 6395–6402, 2013. 35

[28] A. Chauraya, W. G. Whittow, J. Vardaxoglou, Y. Li, R. Torah, K. Yang, S. Beeby, and J. Tudor, "Inkjet printed dipole antennas on textiles for wearable communications," *Microwaves, Antennas & Propagation, IET*, vol. 7, no. 9, 2013. 35

[29] Y. Liu, K. Lau, Q. Xue, and C. Chan, "Experimental studies of printed wide-slot antenna for wide-band applications," *Antennas and Wireless Propagation Letters, IEEE*, vol. 3, no. 1, pp. 273–275, 2004. 41

[30] C. Zhang and A. E. Fathy, "Development of an ultra-wideband elliptical disc planar monopole antenna with improved omni-directional performance

using a modified ground," in *Antennas and Propagation Society International Symposium 2006, IEEE*. IEEE, 2006, pp. 1689–1692. 50

Appendix

Appendix A

Conductive Textiles on the Market

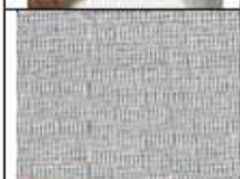
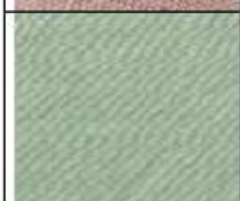
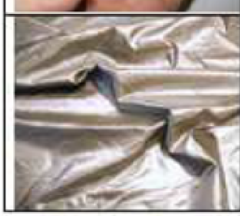
LessEMF.com						
	Product	***Fabric Type***	***Metallic Coating***	***Thickness (mm)***	***Shielding Effectiveness***	***Resistivity (Ω/sq.)***
	Radioscreen	Polyester	Cu-Ni plated	0.09	>50dB 10MHz-3GHz	<0.1
	Argenmesh	Nylon	Ag threads	-	50dB 100MHz-3GHz	<0.1
	Soft&Safe Shielding Fabric	Bamboo	Ag threads	-	>50dB 10MHz-3GHz	<1
	Staticot	Polyester /Cotton	Stainless Steel threads	-	40dB up to 10GHz	1000
	VeilShield	Polyester	ZnNiCu plated	0.018	>40dB	0.1
	RipStop Silver Fabric	Nylon	Ag plated	0.0508	>50dB 20MHz-4GHz	<0.25

Figure A.1: (1) Conductive Textiles Available from LessEMF.com.

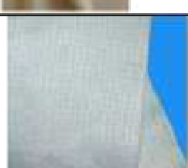
	Product	Fabric Type	Metallic Coating	Thickness (mm)	Shielding Effectiveness	Resistivity (Ω/sq.)
	Cu Polyester Taffeta Fabric	Taffeta	Cu plated	0.08	>75dB 10MHz-3GHz	0.05
	Ni/Cu Ripstop Fabric	Polyester	Ni-Cu plated	0.08	>75dB 10MHz-3GHz	<0.03
	Microwave Absorbing Sheet	Carbon	-	0.445	>25dB 1GHz-10GHz	~3
	SaniSilver	Cotton	Ag	-	>50dB 30MHz-1.5GHz	<1
	ShieldIt Super	Polyester	Ni-Cu plated	0.1143	>60dB 10MHz-3+GHz	1
	Stretch Conductive Fabric	Nylon	Ag	0.4	>30dB 1GHz-10GHz	<0.5

Figure A.2: (2) Conductive Textiles Available from LessEMF.com.

Vita

Dounia Baiya was born in Casablanca, Morocco. After high school she moved to France to pursuit her higher education. She got her bachelor degree in electrical engineering at university of Poitier. She then moved to Paris to study her Masters at Universit Pierre-et-Marie-Curie. During the summer of the first masters year she had the chance to visit USA for three months internship. She worked on antenna simulation and design. She moved after obtaining the masters to the USA where she started a second masters. She is a wife and a mother to Essam and Lillian Elkhouly.