TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ADNAN MEHMOOD

POSSIBILITIES OF A 3D PRINTING PEN IN FABRICATION OF RFID PLATFORMS

Master of Science Thesis

Examiner: Dr. Johanna Virkki and Xiaochen Chen
Examiner and topic approved on 30th May 2018 by the Dean of the Faculty of Computing and Electrical Engineering.

ABSTRACT

ADNAN MEHMOOD: POSSIBILITIES OF A 3D PRINTING PEN IN FABRICATION OF RFID PLATFORMS
Tampere University of technology
Master of Science Thesis, 61 pages
November 2018
Master's Degree Program in Information Technology
Major: Communication Systems and Networks
Examiner: Dr. Johanna Virkki and Xiaochen Chen

Keywords: Eco-friendly, Cost Effective, UHF RFID, 3D Printing Pen, Bisphenol A Free, Flexible Substrates, Bending and Water Reliability, Wearable Antennas, D and E Type Tags, Read Range, Tagformance.

The main objective of this thesis is to use eco-friendly and cost effective material to fabricate radio frequency identification technology (RFID) platforms with wide range of applications. The innovation which is desired is to use only one type of material in making the platforms and even the conductive glue shouldn't be used to make a contact in between the conductive thread and integrated circuitry (IC), the only two components used inside the 3D printed wireless platform. The motive was to achieve enough bending reliability of the platform so it could be used in various wearable applications. There should be a design which have enough bending reliability and should give a good read range result while the tag being used as an application in water. So making a tag water proof is another objective of this thesis to achieve. The aim is to perform two reliability tests, the bending and water and check out the performance of tags after these tests. To make the flexible passive ultra-high frequency (UHF) RFID platforms the used material is 3D printed biodegradable plastic. So in this process a 3D printing pen with non-toxic Bisphenol A (BPA)-free material is used. The platforms are made by hand using 3D printing pen and initially three designs are proposed and drawn accordingly. A bending reliability test is performed and two of the designs sustained the bending test and showed good result so these two designs are finalized for further tags making and testing. In the process of making tag on these substrates one of the problem encountered is that it isn't possible to make the tag on that substrate with proposed antenna specifications due to the design malfunction. So another substrate is designed and bending reliability is checked with test. The bending reliability test is performed at three different cases with different radius of thermago (a round shaped solid material) and epdm (non-conductive paper like material) is used to increase the radius so the conditions might fulfill the desired criterion. Both substrates sustained the bending at the minimum radius of 3.7 cm and maximum radius of 6.3 cm for 3 minutes which is more than enough to use in wearable application. In the process of making tags a conductive thread, IC and BPA free material is used instead of conductive glue. After making the tags of both substrates of type D and type E which are named to make the proper sense of results, each type have three samples for good results and comparison. Tags are analyzed on the basis of read range which are taken for results. Read ranges are taken before bending for both types and after bending at three radius. Then a layer is 3D printed on top of the conductive thread and same tests are performed. Another reliability test is performed in water for both types and after that dry test is also performed to have a comparison of results. Both D and E type tags performed very well in reliability tests of bending and water and even after drying. Both types are analyzed with a layer drawn on the conductive thread. All of the performed tests and results of read ranges for both types are really convincing. Although D type tags have varying results but fair enough to make the decision that achieved results are executable. While E type tags have very constant results in all tests. For measurement purpose anechoic chamber and Tagformance software an RFID measurement system is used to carry out the results of read range. E type tags have average read range of 6 m while D type have average read range of 5 m. The measurements are taken in the frequency range of 800-1000 MHz.

PREFACE

This master thesis “Possibilities of a 3D printing pen in fabrication of RFID platforms” as a mandatory fulfillment in the requirement for Master of Science degree in Information Technology in Communication Systems and Networks major, in the department of Electronics and Communications Engineering at Tampere University of Technology. The research work, implementation and measurements are done in Wireless Identification and Sensing Systems (WISE) research group and laboratory under supervision of Dr. Johanna Virkki and Xiaochen Chen. I would like to extend my heartiest gratitude to my supervisors for their constant guidance, help and providing me proper learning environment. I would also like to thank all the colleagues at WISE laboratory for their input and help.

I am thankful to almighty Allah who helped and gave me strength to complete my degree. I would like to mention all those who helped and kept me motivated throughout this phase of thesis specially Dr. Rizwan, Doctoral students Shoaib, Shahbaz and my friends Junaid, Bilal and Sameen. I would dedicate my thesis work to my parents specially my mother and grandmother.

Tampere, 23.11.2018

Adnan Mehmood

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AM	Additive Manufacturing
RFID	Radio Frequency Identification Technology
BPA	Bisphenol A free
IC	Integrated Circuitry
UHF	Ultra-High Frequency
LF	Low Frequency
HF	High Frequency
UWB	Ultra-Wideband Frequency
BS	Base Station
LOM	Laminated Object Manufacturing
SGC	Solid Ground Curing
SLS	Selective Laser Sintering
SLA	Stereo-lethography
FDM	Fused Deposition Modeling
UV	Ultraviolet
HFSS	High Frequency Structure Stimulator
IOT	Internet of Things
MHz	Frequency
m	meter

1. INTRODUCTION

Additive manufacturing or 3D printing is a method of fabricating the desired products through certain material of specific properties [1]. There are different kind of 3D printers available with different materials being used in printing. The latest and cheapest technology being used for printing is 3D pen which can be used with limited resources anywhere with cheap and commonly available material. The aim of this thesis is to make 3D printed platforms with eco-friendly material being used for RFID tags, tests of bending and water reliability of these platforms and point out the beneficial applications for further research.

With 3D technology the doors are opened to embed RFID tags anywhere and wide range of possibilities in many fields with 3D printed RFID [2]. There is already a lot of research done in 3D printed RFID but the innovation in this research thesis and the objective to attain is that print a material with enough bending and water reliability, use the same material as 3D printed fasteners instead of conductive glue in process of IC insertion in tag. There are a lot of applications which will be revolutionized after introduction of these type of developments in RFID 3D printed tags. An RFID system has readers, tags and servers at back end to process the data which is collected by readers through tags, active, semi passive and passive are the types of tags [3] which are currently used and focus of future research is mainly based on passive tags as it is cost effective so is our thesis aim to have product very cost effective.

The material which will be used in this research is Bisphenol A (BPA) free and it is eco-friendly, biodegradable if it remains in contact with soil for more than 45 days. The dipole antenna contour of the tag will be made by using conductive multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC) and IC used will be of NXP UCODE G2iL series RFID IC [4]. Different type of designed tags would be made to test the bending and water reliability in three different scenarios and each type of tag will have three samples to check the accuracy of results.

In 3D printing process one can easily implant already manufactured subcomponents by common traditional methods and an antenna or sensor can be embedded in 3D printed material which can be visible or invisible [5]. Following this statement the IC and conductive thread of antenna will be embedded on 3D printed substrate with help of 3D fasteners. After the fabrication of tags then these tags will be measured, the measurements are strongly affected by the environment, propagation noise and specific arrangement of setup of measurement [6] therefor anechoic chamber will be used for measurements and Voyantic Tagformance with a computer setup for results observance.

The RFID systems are categorized in four frequency bands which are Low frequencies (LF), High frequencies (HF), Ultrahigh frequencies (UHF) and Microwave and our focus is UHF with range of 860-960 MHz [7] so the measurements will be taken in the range of 800-1000 MHz and results will be analyzed and compared on the basis of measured read ranges.

The measurements of tags which will be performed are named as D, E type for concurrent results although tags named A,B and C were also fabricated but due to some findings those weren't used which will be discussed later in this thesis. The measurements of the tags will be taken before bending and after bending at three radius. The water reliability test will also be carried out for all of the tags with protective layer of the BPA free material on the conductive thread with 3D pen and these tags will be placed in water for few minutes and measurements will be taken. After the water test the dry test will also be performed to compare the results.

The thesis will have following chapters with details, In Chapter 2 RFID is explained with basic concepts and Chapter 3 covers Additive Manufacturing thoroughly. Chapter 4 includes 3D Printing in RFID. Chapter 5 discusses Substrate and Antenna which is detailed with manufacturing and properties of both while Chapter 6 is about Bending Reliability with all the steps followed for testing the bending of tags. Chapter 7 reveals Analysis of Results and it will help to understand the whole story about results. In Chapter 8 the Applications and Future Work of these tags are reported briefly. Finally Chapter 9 Concludes the whole thesis and further research framework will be described.

2. RFID

2.1 RFID Systems

The real idea of radio frequency identification technology and controlling objects remotely was introduced by H. Stockman in late 1948 [8]. The footprints of history of using RFID can be traced out in World War II but wasn't a clear concept of RFID there but then Watson-watt developed the first active identify friend or foe (IFF) system [9] and rest is history now. RFID systems are now an integral part of common people. A simple definition of RFID system is that it consists of a reader, tag and antennas to fluctuate the voltage and create signals to communicate between reader and tag [10]. The antenna of reader might be integrated in the reader or may be separately connected to the reader through a cable but in case of tag the antenna is integrated in the tag and there is one IC which is integrated circuitry connected with antenna.

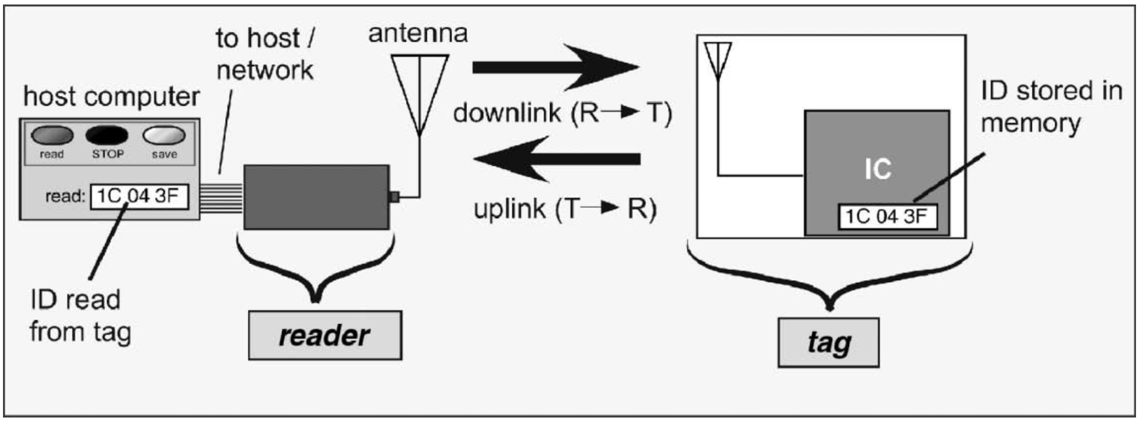

Figure 2-1 An RFID System [10]

So in Figure 2-1 the radio link between reader and tag is defined. It is of two types the information being carried out from reader to tag is called downlink or forward link while the information being responded from tag to reader is uplink or reverse link. In a term of communication system it gives a larger picture of the RFID system that how it works.

2.2 RFID Components

As discussed earlier the RFID is a system which consists of few components and those components are reader, tags and antennas while the tags are further made up of antennas and ICs and different kind of platforms are built for that antenna and IC to be inserted on the platform. The functions of these components will be precisely discussed here.

2.3 Readers

The definition of reader while keeping the RFID in mind is that any device which reads or writes any data to or from the tag. There would be some antenna connected to the reader through an external cable or it will be mounted on the reader and function of that antenna is always to respond the signal from or to tags [11]. There is an application software that is needed to run the reader and process the data. Application gives the command to the reader and receives the desired response and process the data. The fundamental functional blocks of reader are control system and RF interface which are further composed of transmitter and receiver [12]. There are different kind of readers now available in market which have different sizes and even mobile readers are at our disposal. Below is the figure showing different kind of readers, usually fixed reader is fixed with wall or some stand, hand-held reader are mostly used in shops by cashier and mobile reader can be used remotely [13]. Figure 2-2 shows the readers.

Figure 2-2 Different RFID Readers [14]

2.4 Tags

There are three different kind of tags e.g. active, passive and semi passive tags. These tags can operate on different range of frequencies e.g. Low Frequency (LF), High Frequency (HF), Ultra-high Frequency (UHF), Microwave and Ultra-wide Band (UWB). An antenna, substrate and IC together makes a tag, these are few components of tag and antenna is always mounted on the substrate. There are many factors which affect the performance of tags like environment and surrounding materials can have influence on the operating frequency of that tag and many fluctuations can disable the function of tag. Now functionality of commonly used tags will be discussed here.

2.4.1 Active Tags

It is defined as that active tags have their own source of power and it is a small battery which gives the power to IC so that signals can be radiated and communication link can be created between tag and reader. A simple example to understand this concept is that how a mobile transmits the signal to Base Station (BS). With development of new technologies it is obviously creating more opportunities for long distance communication even for 100 m [15]. Active tags are bit expensive to handle because it needs an extra source to power up and perform the whole function. In figure 2-3 the power transmission can be seen.

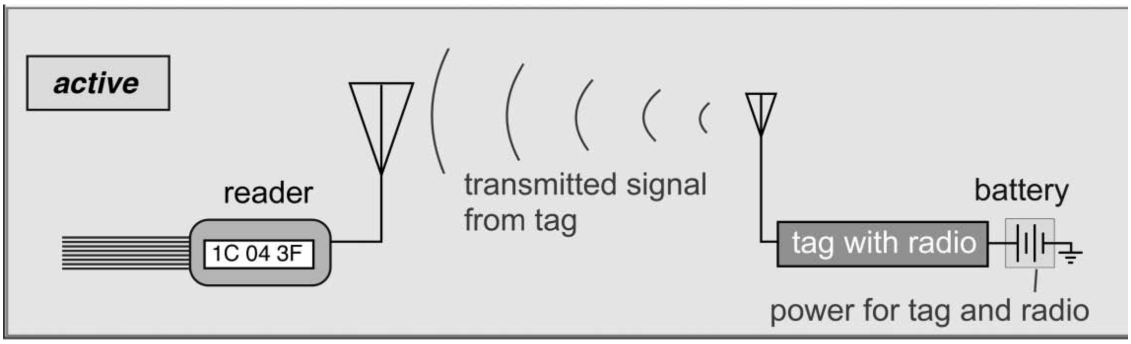

Figure 2-3 Power Transmission in Active Tags [10]

2.4.2 Passive Tags

Passive tags don’t have any actual power source but these tags draw power from reader, reader produces electromagnetic waves and these waves make an electric field around the tag antenna and induces enough current to activate the integrated circuitry. Passive tags are cost effective. The one big benefit of cheaper technology is that more than enough passive tags can be tested in any kind of operation and to check the better feasibility of that function [16]. In figure 2-4 the power transmission of passive tags can be understood.

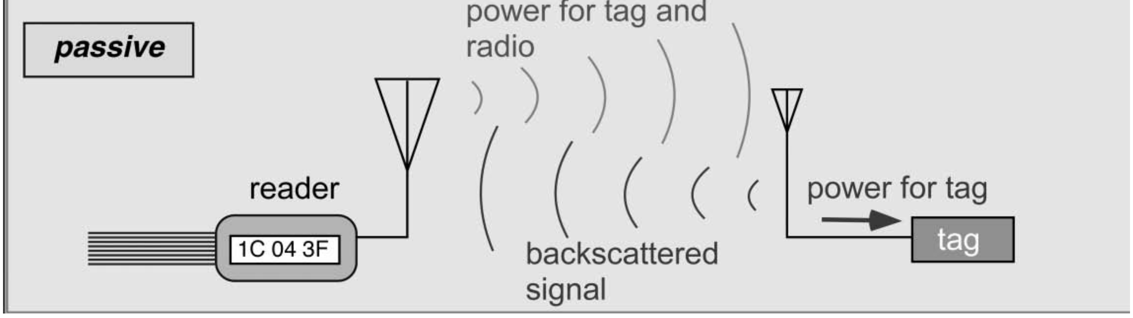

Figure 2-4 Power Transmission in Passive Tags [10]

2.4.3 Semi-Passive Tags

Semi-passive tags power up the IC through a battery source but for communication it draws power from reader. Figure 2-5 explains semi-passive tags.

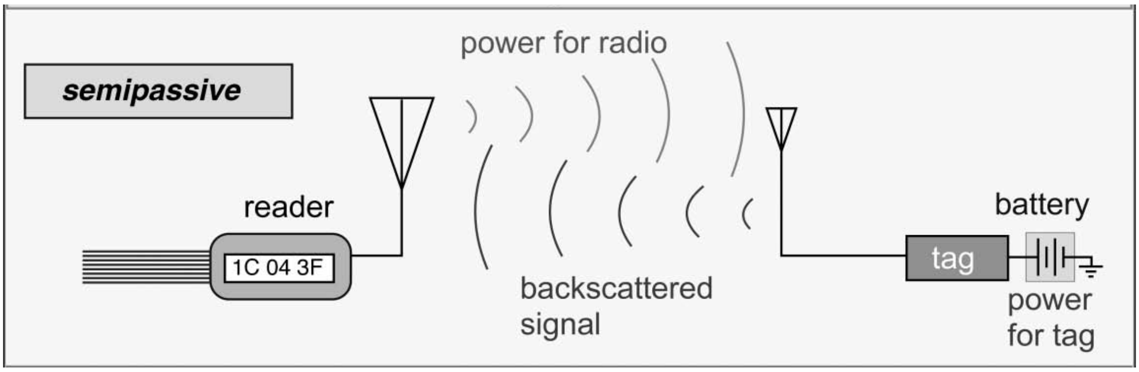

Figure 2-5 Power Transmission in Semi-passive Tags [10]

2.5 Operating Frequency

There are different frequency bands defined in which RFID tags usually operate. Those frequency bands are categorized on the basis of frequency ranges and different names are allocated to them. There is a direct link between the antenna size of tag, frequency and read range of that antenna. Frequency and antenna size has an inverse relation that means if the frequency increase so the wavelength decrease and that eventually leads to the smaller size of antenna. But if long read range is needed to be achieved than size of antenna is also needed to be increased.

The frequency bands are categorized as LF, HF and UHF which are currently excessively used in RFID field. The frequency range and the active read range of the tags with specific read ranges is explained here in table 2-1.

Table 2-1 RFID Frequency Bands and Read Ranges [17]

Frequency Band Spectrum	Description of Frequency Band	Read Range
125-134.2 kHz	LF- Low Frequency	Up-to 0.5 m
13.55-13.56 MHz	HF- High Frequency	Up-to 1 m

858-930 MHz	UHF- Ultra High Frequency	1 to 10 m

Antenna design for the tags highly depends upon the operating frequencies. At LF the antenna needs hundreds of coils to produce enough voltage for operation. While antennas operating at high frequency usually needs 3 to 6 turns of coils to induce the voltage. The UHF antennas have half wavelength size [10]. Below is the figure 2-6 for better idea.

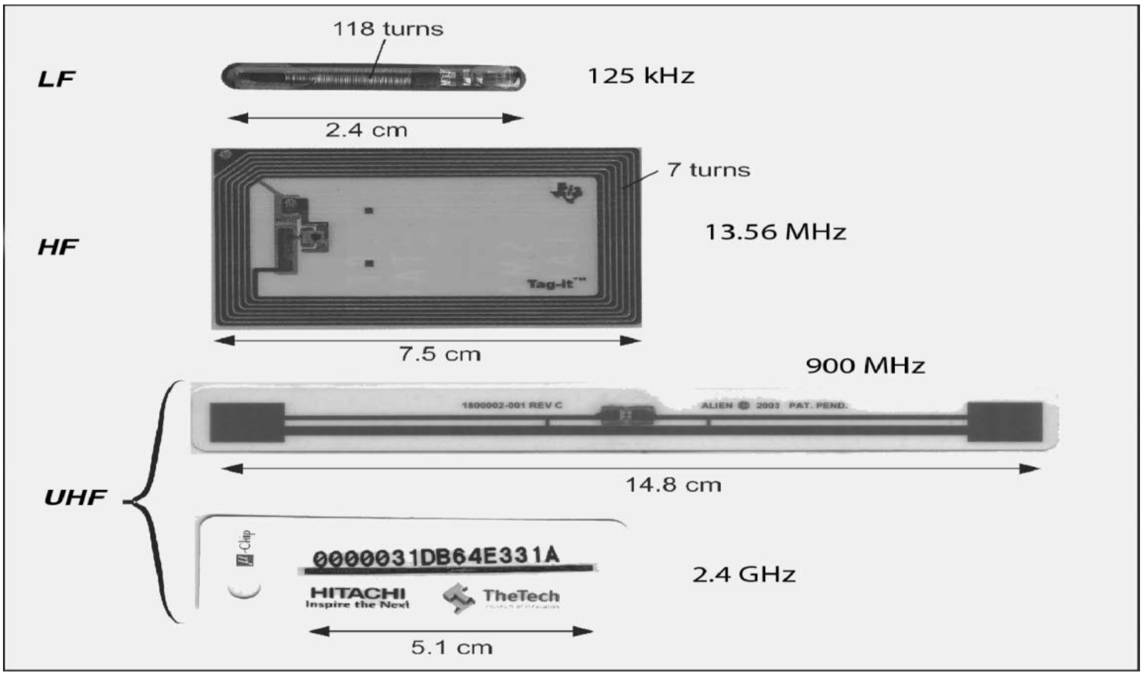

Figure 2-6 Antenna Design w.r.t Operating Frequency [10]

2.6 Read Range

The stored information on the IC of tag which can be read at the maximum distance through reader is called read range [10]. It is the simplest and easiest performance indicator of tag to understand the capacity of performance and compare the results. In this thesis the performance of all the fabricated tags has been evaluated by comparing the read ranges of tags. There are some important factors which will increase the performance of tag in term of read range and those are polarization, optimizing tag antenna gain, matching of impedance and directionality of antenna tag [18].

2.7 System of RFID Measurement

The measurements in this thesis are taken by using the voyantic tagformance measurement system for UHF RFID and all the fabricated tags were analyzed in anechoic chamber which is attached to the Tagformance and a computer system to view and process the measurements. The figures 2-7 and 2-8 show the whole measurement system.

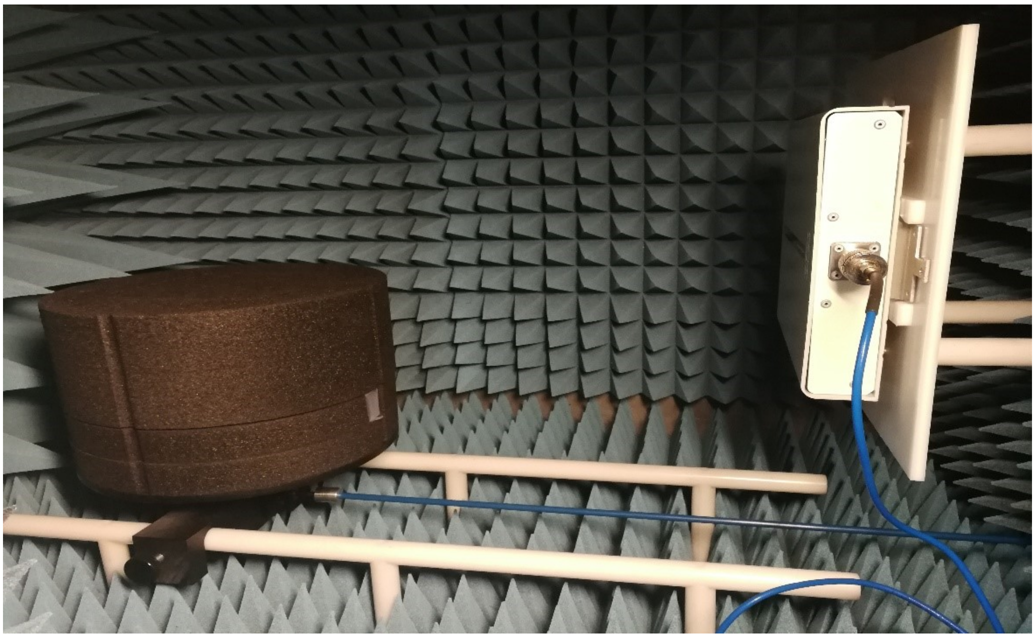

Figure 2-7 Anechoic Chamber

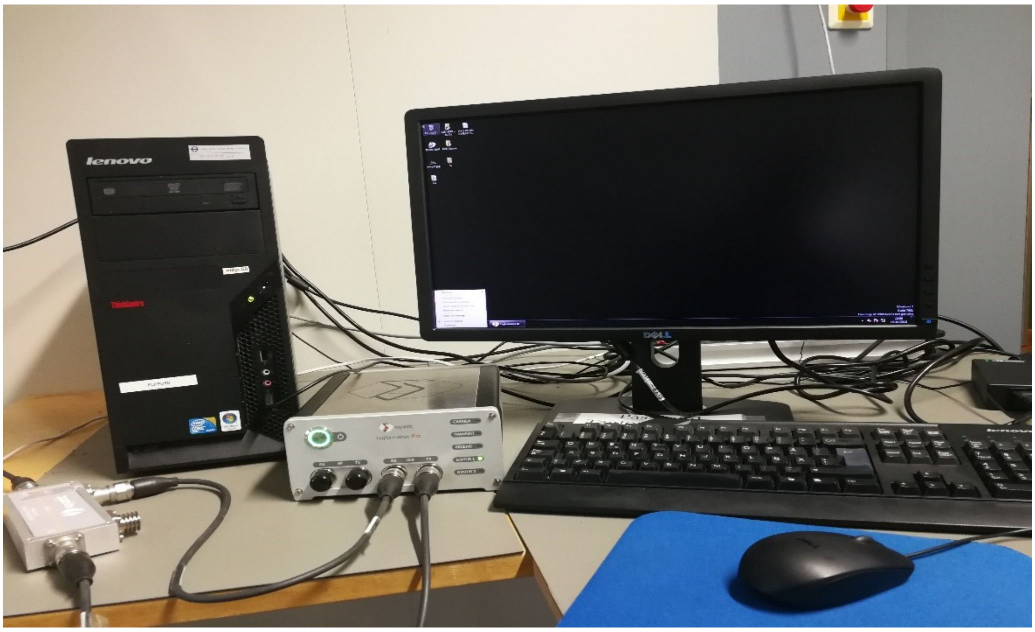

Figure 2-8 Tagformance and Computer System

So the linearly polarized antenna of reader can operate in the band of 800-1000 MHz frequency. First the system is calibrated through a reference tag which measures the required power the IC of tag to activate and all the losses of antenna, cable and other connectors. The target tag which is needed to be studied is placed at same position where the reference tag was placed. In this system the radiation pattern of the tag at a certain frequency can also be measured. In this thesis the read ranges will be analyzed for number of tags and those highly depends upon the path losses and sensitivity of IC that means how much wake up power is needed so this system measures the read range of tag based on these factors [19].

3. ADDITIVE MANUFACTURING

3.1 Definition

The additive manufacturing (AM) referred to the term of process in which layers are combined to the layers to make a specific design or product. In simple words the process of fabrication of parts by adding material into layers. To be specific about the antennas the process of inserting the conductive material into the substrate or manufacturing the substrate itself [1]. The additive manufacturing process is also termed as rapid prototyping which is a quick process of creating or fabricating an object with a material, it also refers to the physical modeling of a digital design through a machine [20].

This process is very accurate and fast way of making the products. It is more convenient way of making the antennas as the material used in antennas is conductive of nature which is expensive, due to the accuracy of the process used less material is used in fabricating antennas through additive manufacturing. This process has wide range with variety of machines and materials available for printing and these machines use certain software in which the design of a particular product could easily be optimized and can be printed with high accuracy so it is very reliable method while after printing the product would need final finishing. So the product is directly made through digital idea.

3.2 History of 3D Printing

The typical start and traces of additive manufacturing can be found in 1950's and 1960's but the boom in this field was seen in 1980's with the development of lasers, controllers and computers in this manufacturing technology [1]. In the era of 80's a lot of work was going on in 3D printing around the globe and the main idea behind the whole process was to deploy layers by layers a material with a machine and consolidate an object in physical shape. Laminated Object Manufacturing (LOM), Solid Ground Curing (SGC) and Selective Laser Sintering (SLS) were the few processes initially used by three different companies and in this competition only SLS survived which further developed to the 3D printing in 2000's.

3.3 Different Processes

There are many manufacturing process being used. These fabrication processes are being revolutionized with the advancement of technology and needs of the day. There are a lot of processes being used e.g. vat photo-polymerization, power bed fusion, material extrusion, material jetting, binder jetting and direct energy deposition [21]. Each process has many technologies which are currently into use and are named differently according to the nature of the machine and material being used in that technology. To make this introduction to different technologies very short only few commonly used technologies will be explained precisely.

3.3.1 Stereo-lethography

These type of printers use an ultra-violet (UV) resin and UV laser producing equipment to form a solid object [22]. In this process a built platform is dipped in the tank full of photopolymer resin and after dipping the built platform a UV laser which is connected inside the chamber cuts down a cross sectional area and soon a layer is formed and solidified through laser than another layer of resin flows from downside of the chamber. This process is repeated again and again so the object is formed in a solid shape after repeating these steps multiple time. Direct light processing (DLP) and Continuous DLP are some other technologies which are used in this process and those are almost identical to the above method.

3.3.2 Selective Laser Sintering

SLS is the most promising technology of 3D printing giving the excellent results and this technology uses plastics and polymers as material and laser power source to produce the layer by layer a solid object [23]. The process is performed through spreading the powder on a built platform and then a laser is used to solidify and clean the edges of the object, this process is repeated again and again. So layers are spread over other layers and laser jet is used to perform the action. After completing the process the object is separated from powder. The product is ready after post processing and cleaning [21]. Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are also similar methods like SLS.

3.3.3 Fused Deposition Modeling

The setup procedure and operating time of an FDM printer is much smaller than SLA printers [22]. This technology is commonly and widely used in 3D printing. A solid thermoplastic material is used, which is in a shape of filaments and are used to build the objects [21]. A heated nozzle is used to melt down the solid filament which is passed through the nozzle and this nozzle is used to draw the desired object. The nozzle moves continuously and layers are drawn at each other to form the object’s shape. So the material cools down after some moments and gets the solid shape. It is perfect and accurate method to draw any object.

3.4 Process Used in Thesis

The method used in this thesis is quite a new and whole process is handled manually and there isn’t any program involved. A 3D Printing pen is used with a BPA free material which comes in a solid and stick like form. There is no operation of any machine involved because the pen is handled with a human hand. The pen name is 3Doodler and price is around 30 $ with a round shape which is easy to handle, there is a light on the pen which indicates the battery life and when the button is pressed it indicates the material is ready to flow. Figure 3-1 shows 3D printing pen.

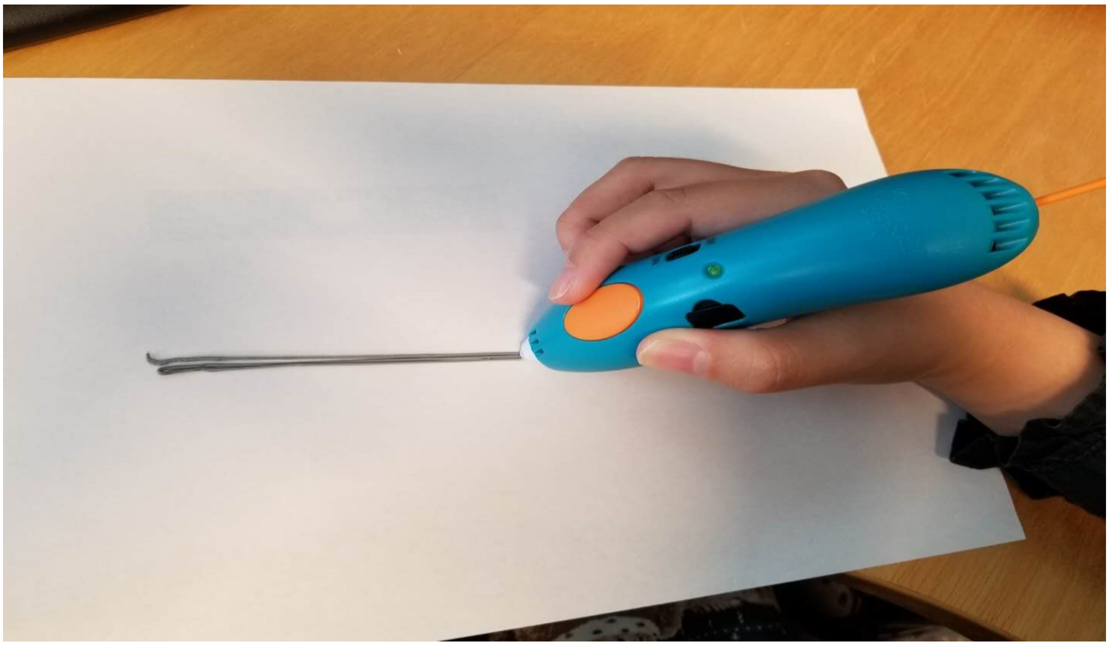

Figure 3-1 3D Pen Used for Fabricating the Substrates

The pen has a system like FDM in which material passes through high temperature and it is melted down which is further developed into the desired shape and after few seconds of cooling down the material gets the solid shape. It is easy to recharge and charging cable comes with the pen. It's cheap, reliable, easy to handle and can be carried out anywhere.

3.5 Steps of Manufacturing

DfAM design for additive manufacturing technology is used to build the product through 3D printing [24]. The first step in AM is always to finalize a design according the product description, the proposed material and the equipment which is being used in this process. If the product gives desired results then there is no need of further modification and the results are not like the expected one then there should be redesigning and modification in method of implementation.

The designing can be conceptual, a random idea, designing through computer aided drawing (CAD) tool or drawing by hand and making a sample of product and test the product either results are achieved or not. After the selection of a final design the product is made through printing process. In this thesis different designs were proposed depending upon the orientation of the material being spread over the sheet which will be discussed later in this thesis.

3.6 Fabrication Process

It is explained precisely in previous heading that how the manufacturing process yields to the final product. But here the detailed fabrication process of this thesis is explained. 3Doodler is a printing pen used for making the substrates for RFID tags to achieve our desired results. Any fabrication process depends on the manufacturing capabilities and the available resources, the resources include printing material and equipment of printing.

This process is completely manual, the designs of substrates are drawn on the paper and then these designs are printed through printing pen and followed by the bending tests to check out the reliability of substrates. Which further resulted in many findings related to the design malfunction of the substrates and tags making process. So in using 3D printing pen the key to the complete process is that how the product is designed keeping in mind the real environment and objectives to achieve. The complete process is explained later in this thesis.

3.7 Printing to 3D Printing Development

The history of printing is quite old, people used to carve things on the dry skins of animals and make different shapes of surroundings. So the printing was being done even before 3000 BC. Archeologists have found the footprints of many objects which were molded and made by mud at that time so it can be said the concept of 3D printing is carried from those findings. In this age 3D printing is seeing a boom in the market and a lot of developments can be seen on daily basis. The developments are based on material, selection of a process depends on the results to be achieved and available manufacturing capabilities.

3.8 Printing Machines

It is explained earlier that there are different type of printing methods which are used to print out the objects so based on those printing methods there are different printing machines available. Those methods are explained in detail so here only few printing machines will be discussed. These printing machines differ each other on the basis of cost of printer, quality of printing, speed of printing, capability of printer and the expectation of user [25].

Figure 3-2 Different Type of 3D Printers [26]

The figure 3-2 shows different 3D printers. These are the few printing machines which are being used commonly in this era. Though more and fast developments are underway as well regarding 3D printing technology. Each company is trying to build cheaper and small printers.

3.9 Advantages

By using 3D printers quick and accurate designs are delivered. The objects are built at higher speed and it is one step manufacturing that only needs a Computer-aided Design and just start printing the object with provided material. It is really a cost effective method because it includes a cost of printing machine, the printing material and very low cost labor to operate the printing machine and there aren't special skills needed from labor because one just need to press the start button and rest of the processing is handled by printing machine itself. Sometimes the printed objects need post processing as well. The complexity of design can't be compromised because through CAD tool one can design as complex design as one wants and printer can handle the complex designs very well.

4. 3D PRINTING IN RFID

4.1 Basics

By using radio frequency wireless identification technology the items and objects are tracked and sensed through electromagnetic interaction [27]. RFID was being used only in tracking, like the application of retail and real time tracking but now the applications are extended to Internet of Things [28]. There is a huge potential of improvement in manufacturing methods of RF components while using additive manufacturing [29]. To reduce the total cost of an RFID system the improvement is needed to bring up the low cost material for substrates and conductive materials as well. 3D printing is the new technology which is being used to make the RFID tags. In this chapter 3D technology in RFID will be explained.

4.2 Printing Materials

The traditional available materials are non-flexible [30] so these are not suitable for the wearable applications and in flexible electronics. Paper, polyester, polyimide, ninjaflex and kapton are available materials to be used to print the substrate. The objective of this thesis is to make the perfect flexible substrate with 3D printing technology. So a new material is tried to print out the substrate and achieve the flexibility as much it is possible. The results are really promising. For this purpose the Bisphenol A free material is used and characteristics told by the manufacture are if the said material remains in contact with soil it will decompose itself in 45 days. The material is eco-friendly.

4.3 Printable Structures

Radio frequency identification technology has two concepts of printable structures, one is printing the substrate and other is that printing the conductive material on some ready-made substrate which can be a paper or any other material. In this thesis the substrate is 3D printed with 3D printing pen and then antenna is fixed over the substrate through fixers of same material with 3D printing pen. One example is RFID tags with inkjet printer are printed on paper, wood and cardboard material [31]. Printable structures and their characteristics highly depend on the material and method used and the objectives which are likely to be achieved.

4.4 Electromagnetic Properties

The performance of an RFID system is usually measured in terms of sensing power of the reader and tag that at how much distance it can sense the tag [6]. The communication between tags and reader is done through electromagnetic waves [32]. So the electromagnetic properties of the materials which surround the tag affect the ability of communication of tag [33]. The transponders convert the electrical signal into electromagnetic wave and on reader side it convert backs the electromagnetic wave into electrical signal. These electromagnetic waves travel in certain frequency band which is standardized internationally. This thesis is about the study of UHF RFID tag.

4.5 Permittivity

Permittivity is an electrical property which remains between intensity and displacement of electric field, it is focused to achieve actual results [34]. It is an inverse relation between relative permittivity and dielectric constant.

4.6 Flexibility

The advantage of using 3D printing technology is that a complex structure of any kind can be built by using 3D manufacturing methods. It is a mechanical property associated with the material used. Different materials are being used in 3D technology and each material has a different flexibility reliability after being printed, the Ninjaflex is light weight and strong material and has high flexibility [35]. It is much needed to achieve enough flexibility of the RFID tag so variety of applications can be introduced and cheaper methods might be introduced. One of the objective of this thesis is to achieve enough flexibility of the substrate which is being used.

4.7 Advantages and Benefits

Introducing 3D printing technology in RFID was a breakthrough and a new boom in different technologies where complex structures were really difficult to produce and implement the desired results. This method has increased the possibilities of using different materials with different properties. It has reduced enough time of production and really a cost effective method. This process is highly accurate and it has decreased the risks and errors during manufacturing. By using 3D printed technology it gives a unique possibility that keeping in view 3D object the RFID tag can be built in exact that shape.

5. SUBSTRATE AND ANTENNA

5.1 Substrate

The part of RFID tag which holds different components together and provides a base for complete tag. The antenna is fixed on the substrate and then IC is embedded in the antenna to make a tag. It is always kept in consideration that used material in substrate manufacturing should be flexible enough and target application should be in mind while selection of material for substrate [36]. The aim while selecting a substrate should be that it may easily withstand the environmental effects and shape may not get distorted while performing different tests on the substrate. Ethylene propylene diene monomer, Polyvinyl chloride, Plastic, Paper and Polyesters are few examples of materials which are being used in production of substrate.

The substrates are differentiated on the basis of material used, the properties of material, method used in printing the substrate and reliability tests which are supposed to be performed on the substrates. In this thesis to gather enough data for the purpose of comparison and deep study of the said objective there were three designs proposed initially and based on those designs three shapes of substrates are printed by using 3D printing pen. These three designs were printed initially and bending reliability test was performed on them. The findings of this test lead us to print the substrates of our desired shapes.

5.2 Antenna

It is a transmitting and receiving system which is designed to radiate and receive the electromagnetic waves [37]. The antenna used in making tags is dipole with a matching slot in the center.

5.2.1 Dimensions and Specifications

The dimensions and specifications of used antenna in this thesis are explained here. The shape of dipole antenna can be seen in following figure 5-1.

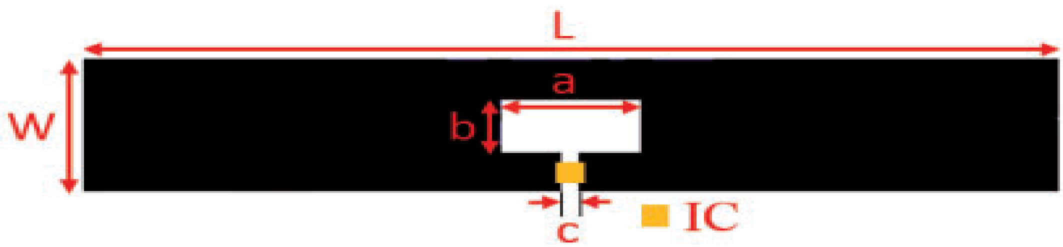

Figure 5-1 The Shape and Structure of Antenna [38]

Table 5-1 Dimensions of Antenna [38]

a	b	c	W	L
14.3 mm	8.125 mm	2 mm	20 mm	100 mm

The table 5-1 gives us the complete details and dimensions of the antenna used in this thesis for tags making.

5.3 Antenna Manufacturing

The dipole antenna in this thesis has been manufactured by using conductive multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC) [4] on already made substrate. The conductive thread is fixed on the substrate with 3D fasteners at corners and thread has circled four times of the basic length of the antenna. The total length of antenna design is 29.2 cm so we have used four times 29.2 cm so that the probability of error may reduce to zero because the whole process has been done by hand and there is very high possibility of error.

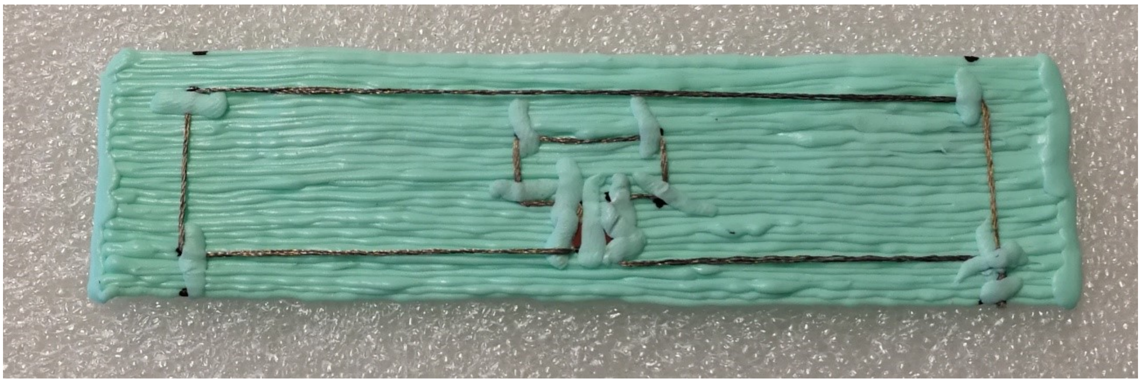

Figure 5-2 The Antenna Fixed on Substrate

Figure 5-2 shows fixed antenna. The method applied is manual, carried out by hand and using 3D pen to fix the antenna with 3D fasteners of BPA free material. The IC is also fixed with 3D fasteners instead of conductive glue which was one of the objective to achieve. To best of our knowledge it is first time that uniqueness we have achieved of fixing an IC on the antenna through same material which is used to fabricate the substrates, before that conductive glue is being used as a conventional method which is quite hectic because it takes around 24 hours to dry out and testing remains pending until the IC is dried so for the very first time with this innovation of fixing IC through 3D fasteners it has been possible that IC is fixed within 3 minutes and dried as well which conveniently allow to test it within minutes and this method is really cheap and easy to follow. The integrated circuit belongs to NXP UCODE G2iL series [4].

6. BENDING RELIABILITY

6.1 Definition

The flexible and stretchable substrates have changed the concepts of usage of wireless technology [39]. The flexibility of substrate that how much it can bear the force before it breaks down or the change in structure occurs is called bending reliability. The bending reliability depends on the properties of material used and method of manufacturing.

6.2 Method and Equipment Used

A round shaped thermago material with a radius of 3.7 cm has been used for carrying out the bending reliability of tags manufactured for testing. Different tags are manufactured and bending is done for each tag by fixing the tag on thermago with scotch tape for 3 minutes at least. This test has been done on all tags.

6.3 Types of Substrates

Three different shapes of substrates are manufactured and each substrate has its own uniqueness of design which differs to other two substrates. Three different designs are drawn on the paper and then three samples are printed with 3D printing pen. All of these differ in shape and due to shape the bending flexibility has been changing in different scenarios.

One kind of substrate has been printed in horizontal axis and layers are in horizontal to each other which further draws the full substrate while in second design there are three vertical columns at a distance of 2 cm and in between those columns there are horizontal blocks of layers. In third design there are two open squares in center of substrate and remaining part of substrate is horizontally fabricated.

6.4 Cases and Results

Three types of tags are bended at three different radius, the radius of thermago round shape has been increased with EPDM material. We have three situations 6.3 cm, 5 cm and 3.7 cm and at each radius all the substrates have been bended for three minutes at least. The results and findings of each substrate are described here in detail. Figure 6-1 shows bending test performed.

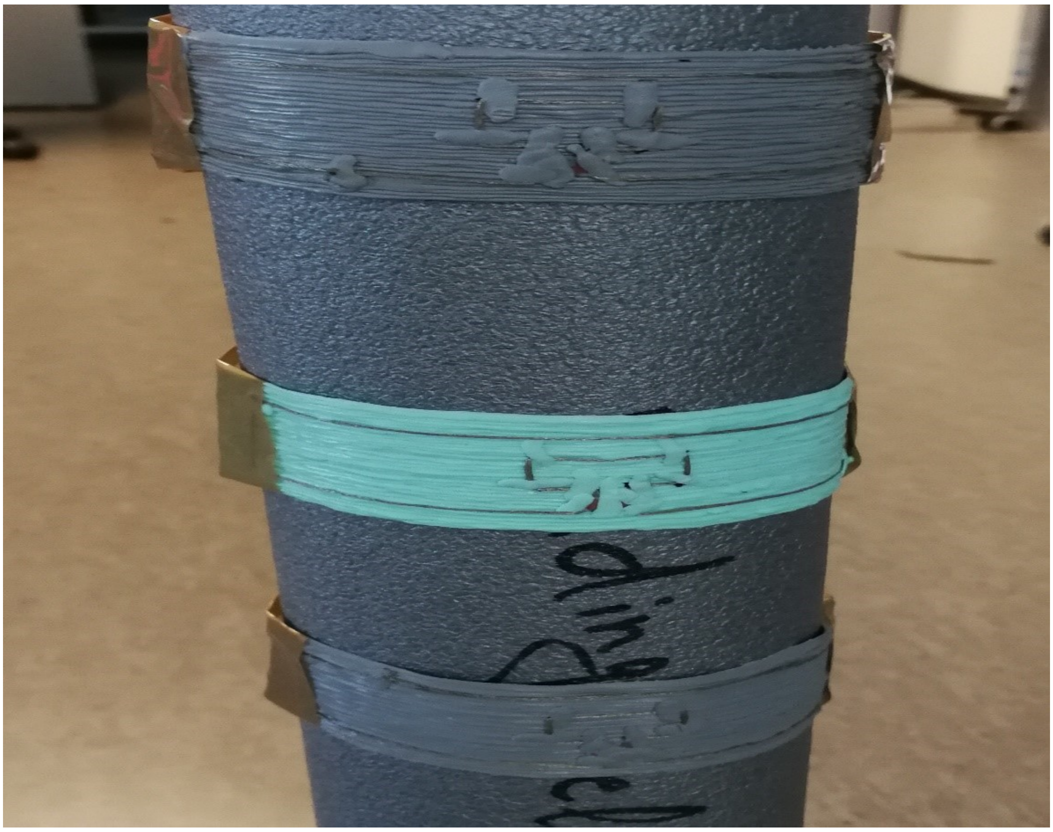

Figure 6-1 Bending Testing Performed

6.4.1 Type ‘A’ Substrate

The shape of type ‘A’ tag can be seen in following figure 6-2.

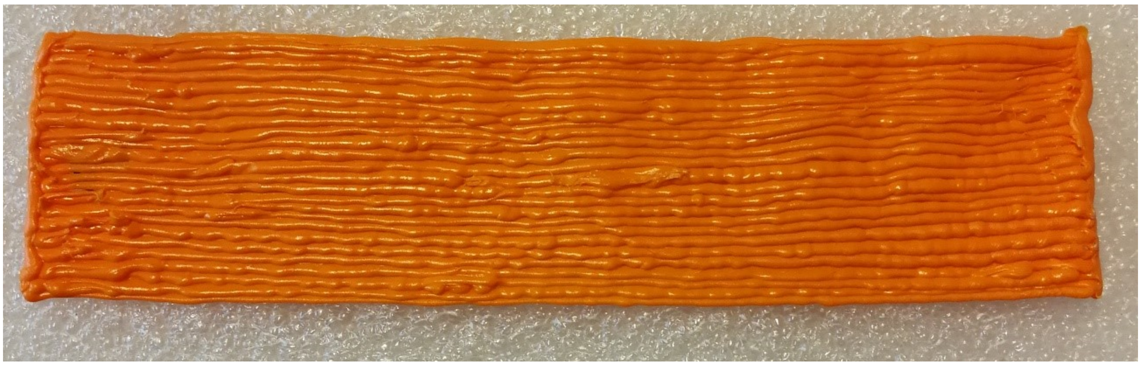

Figure 6-2 Type 'A' Substrate

Table 6-1 explains the bending reliability results for ‘A’ type substrate and is detailed with information that how long this type of substrate has sustained the bending and the shape of substrate isn’t changed due to bending.

Table 6-1 Results of Bending for 'A' Type Substrate

Type	6.3 cm Radius	5 cm Radius	3.7 cm Radius
A1	3 min	3 min	3 min
A2	3 min	3 min	3 min
A3	3 min	3 min	3 min

It is clear that three samples of this type of tag has sustained the bending reliability that means it doesn't break after bending for 3 minutes in all three situations. So this type of tag has been finalized for further testing and tags making.

6.4.2 Type 'B' Substrate

The shape of substrate designed of this type has been presented here in following figure 6-3.

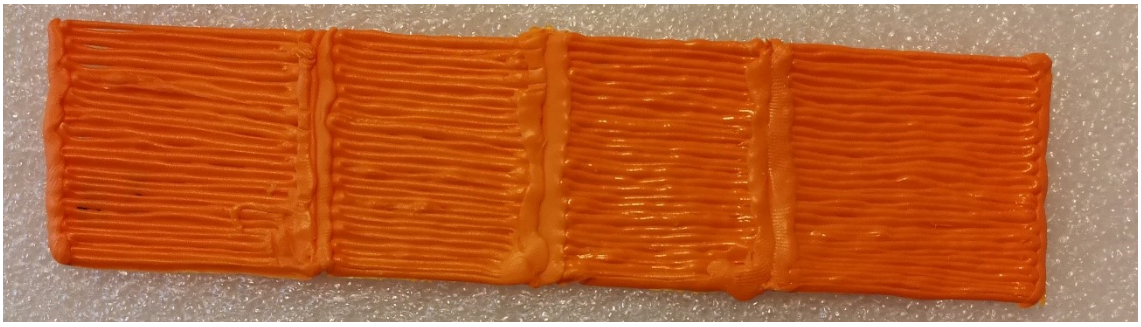

Figure 6-3 Type 'B' Substrate

Table 6-2 is detailed with the data of 'B' type substrate that how much and for how long bending has been sustained.

-Table 6-2 Results of Bending for 'B' Type Substrate

Type	6.3 cm Radius	5 cm Radius	3.7 cm Radius
B1	3 min	3 min	Broke down
B2	3 min	3 min	Broke down
B3	3 min	3 min	Broke down

Three samples of this shape of substrate have been printed and bending reliability of each tag has been checked for all the given radius for three minutes at each situation. These tags have successfully sustained the bending reliability till the radius of 5 cm and at the radius of 3.7 cm these tags have broken down. So this type of tag has not been carried out for further testing and tag making.

6.4.3 Type 'C' Substrate

Type 'B' substrate couldn't sustain the bending so another design has been proposed and printed to check the bending reliability. The shape has been shown in the following figure 6-4.

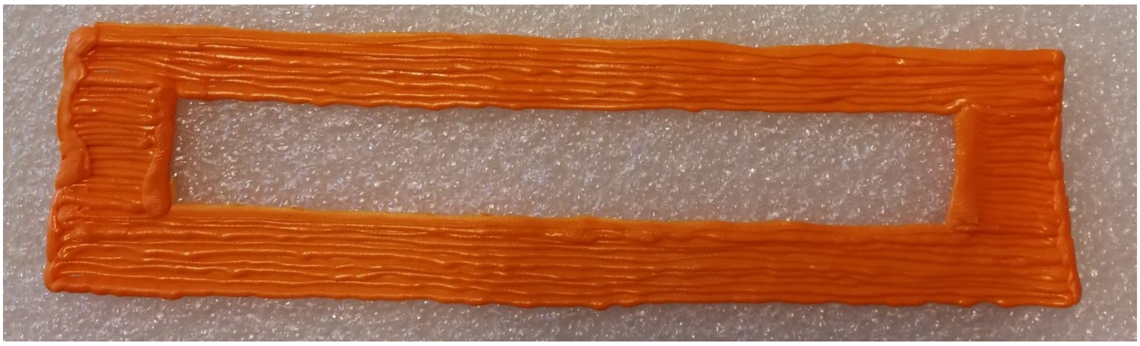

Figure 6-4 Type 'C' Substrate

The table 6-3 explains the bending reliability test for 'C' type substrate with its comprehensive results.

Table 6-3 Results of Bending for 'C' Type Substrate

Type	6.3 cm Radius	5 cm Radius	3.7 cm Radius
C1	3 min	3 min	3 min
C2	3 min	3 min	3 min
C3	3 min	3 min	3 min

This substrate hasn't changed its shape and sustained the bending in all situations for three minute so this type of substrate has also been finalized for further study.

6.5 Final Selection of Substrates

It has been found through study that type C tag has design malfunction and antenna with proposed specifications couldn't be printed on the substrate, so this type of substrate has been redesigned and carried out all the bending reliability testing and that successfully passed the testing.

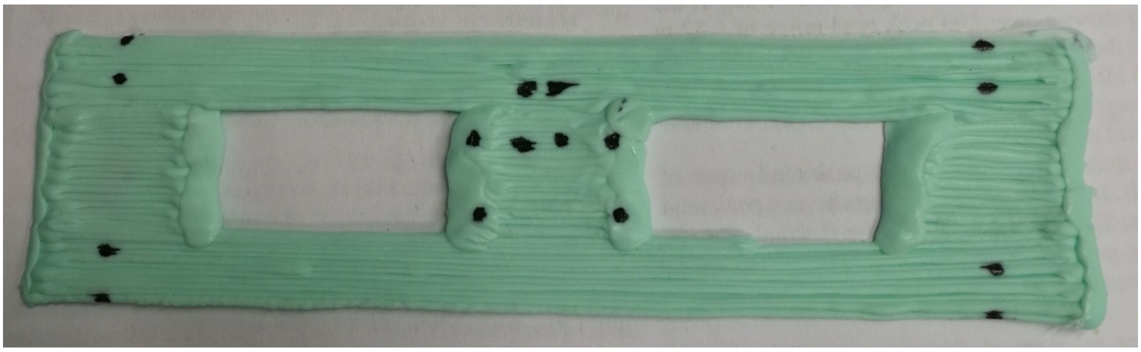

Figure 6-5 Type 'D' Substrate

The substrate in figure 6-5 has been taken instead of substrate type C for further study. There is also some modification made in design of type A substrate just to match the size of type D so it may not differ in size. So new type of tag has been named ‘E’ and it is just a replica of A type substrate with reduced size. So we have type D and E finalized for further study and testing.

7. ANALYSIS OF RESULTS

7.1 Introduction

This chapter is about complete results and findings of the tags which are analyzed at different stages. Two types of tags are under study for reliability tests of bending and water. Three samples are manufactured for enough data so that could be analyzed and compared. The system used for measurement has already been discussed earlier in this thesis. Two types of tags have been manufactured, one type is named D and other one E. While each type has three tags named as D1, D2, and D3 for D type and E1, E2 and E3 for E type.

7.2 Type 'D' Tags

This section has detailed data on measurements of D type tags which covers all the results of bending tests and comparison of three samples of this type.

7.2.1 Before Bending

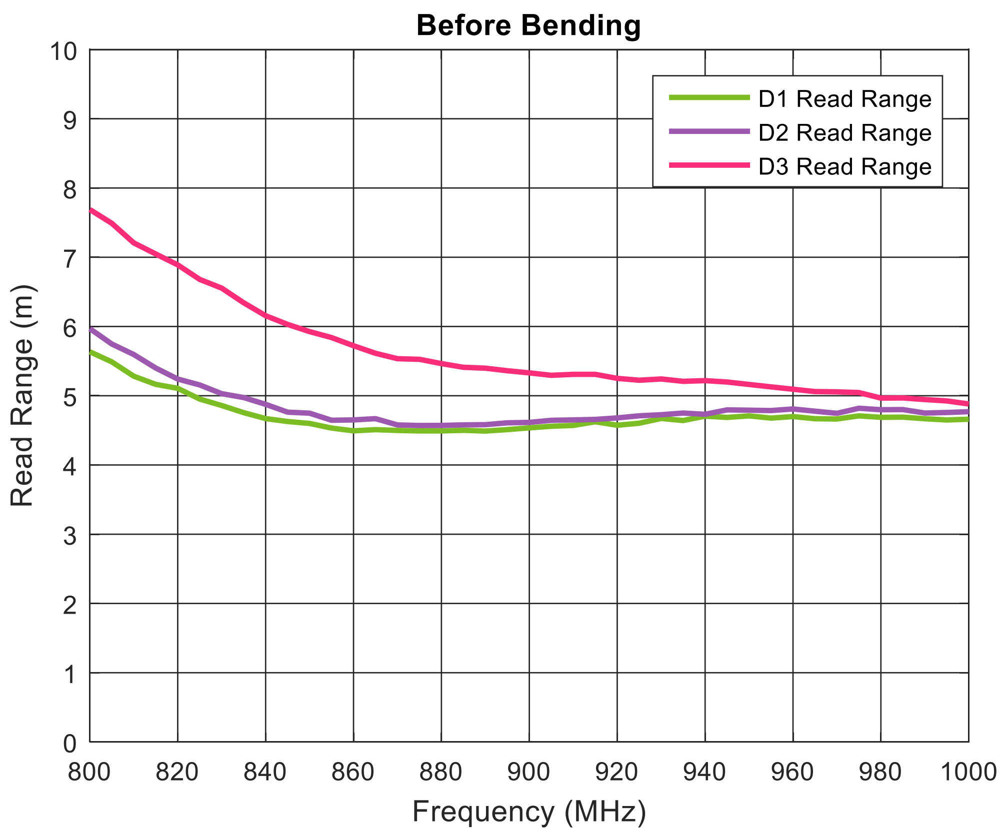

Figure 7-1 D Type before Bending

The figure 7-1 shows graph. The measurements are taken in range of frequency (800-1000) MHz, D1 tag has given the read range starting from around 8 m and it is decreasing until 1000 MHz frequency with a closing read range of around 5 m. Tag D2 has a starting read range of 6 m and showing a little decreasing behavior and final reading of read range is around 5 m at 1000 MHz. The same behavior is being showed by D3 tag which has a starting read range of 5.5 m around and decreased to around 4.5 m. All of three tags are showing a sharp decrease from 800 MHz until 860 MHz while starting from 860 MHz the tags have a kind of constant read range behavior until 1000 MHz. So it can be said that between (860-1000) MHz the tags have more stable read range. Most important point is that all of three tags have a broad difference of ranges at starting frequency of 800 MHz while near to the 1000 MHz all tags have almost same read range.

7.2.2 After Bending

There were again three scenarios created for bending and radius of bending material was kept for 3.7 cm, 5 cm and 6.3 cm respectively so we have three readings for each type. Each tag was bended for 3 minutes at least on the bending material and after bending the tags were then measured again through tagformance. The results of measurements of each tag are attached here and analyzed separately.

7.2.3 Bending at (6.3 cm) Radius

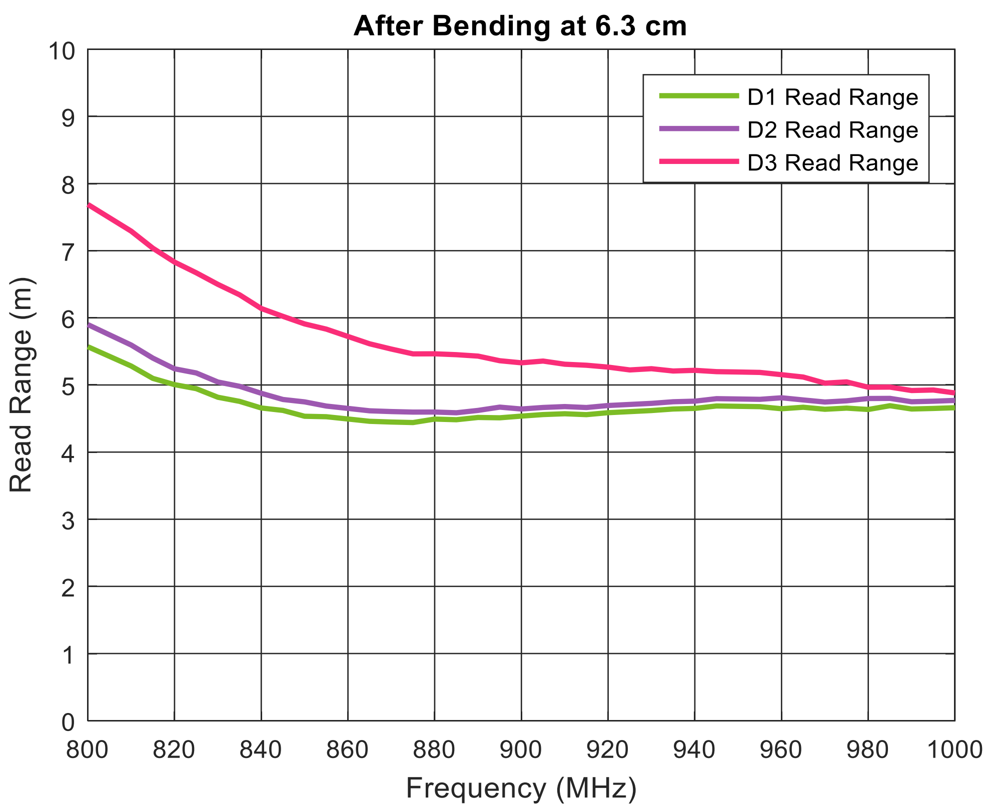

Figure 7-2 D Type after Bending at 6.3 cm

The figure 7-2 shows graph. It is obvious through the graph that there isn't any impact of bending on all of three tags while bending at 6.3 cm. So we can say that tags have almost same read ranges as of the initial read range of tags without bending.

7.2.4 Bending at (5 cm) Radius

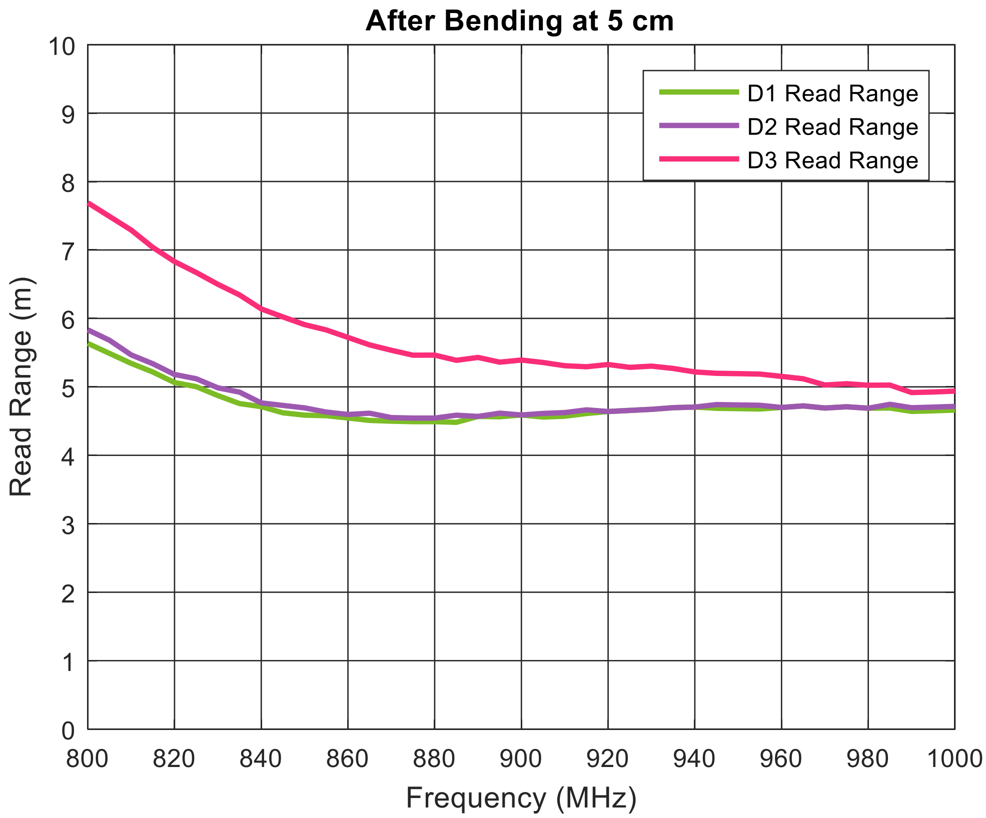

Figure 7-3 D Type after Bending at 5 cm

The figure 7-3 explains graph. In this case the read ranges of tags D1 and D3 have remained same as those were earlier in both cases while D2 has showed the improvement and gained back the read range as it was in the case of without bending. It can be said that somehow while bending at the radius of 5 cm the structure of antenna got the original shape.

It can be noted that all the types have decreasing behavior of graph in the frequency range of 800-860 MHz which is then almost constant and showing a straight line the frequency range of 860-960 MHz. The frequency range of 860-960 MHz is our desired range where these tags were supposed to have a constant behavior as these tags are manufactured for UHF range. In the frequency range of 960-1000 MHz tags are showing almost constant behavior.

7.2.5 Bending at (3.7 cm) Radius

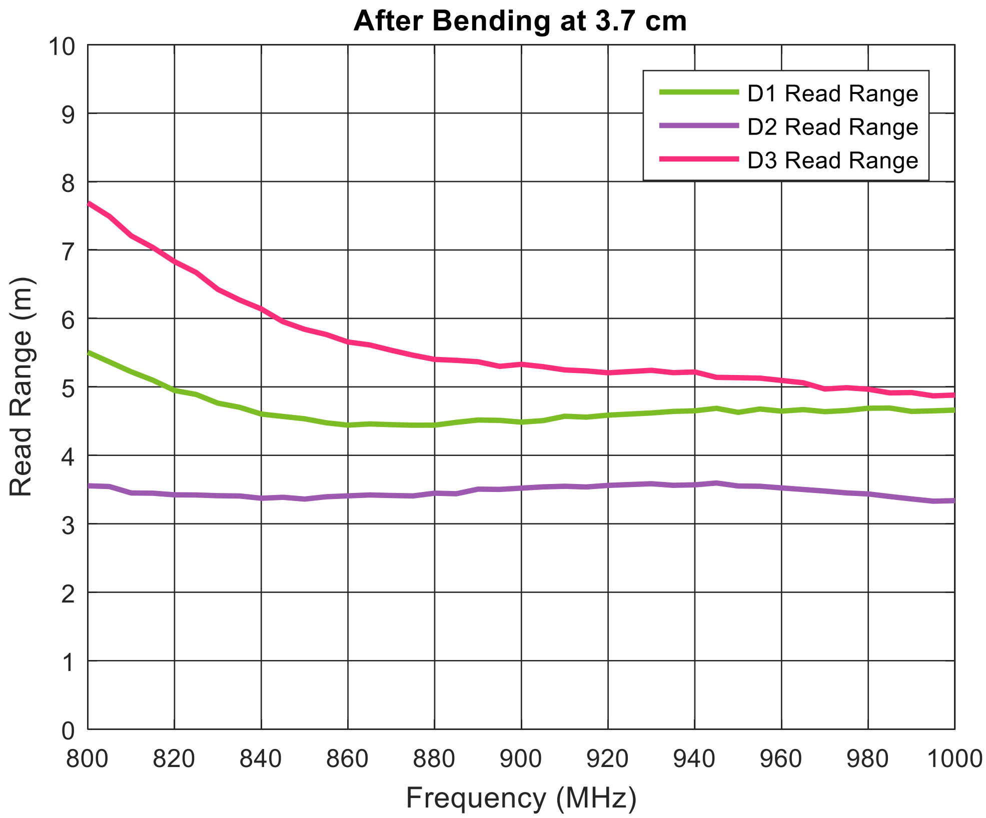

Figure 7-4 D Type after Bending at 3.7 cm

The figure 7-4 shows graph. Tag D2 had very different behavior in comparison to the other two tags D1 and D3. The read range of D2 is subsequently different as compared to the read range of D2 without bending. It has decreased to 3.5 m, although it remained constant throughout the frequency band. Tags D2 and D3 have almost same read range which was in case of without bending. So it can be said that while bending the structure of antenna of tag D2 has been damaged due to which the read range has decreased.

7.2.6 Layered Tags

Then a layer was made on the conductive thread of antenna and IC as well and those were well water proofed. The aim of this process was to make it sure that no water may intact with antenna so the tag can be used in water and performance of that tag can be analyzed. This layer is 3D printed layer with same material of BPA free which is used to manufacture the platforms for the tags.

The layer is drawn in such a way that whole antenna and IC becomes invisible and it is also kept is account that layer shouldn't be much heavy as it would create problem while bending and cracks might appear in the process of bending reliability test. So the process of printing is kept smooth and taken out with care that structure of antenna and IC may also not get distorted and our results will not meet the criterion.

7.2.7 Before Bending

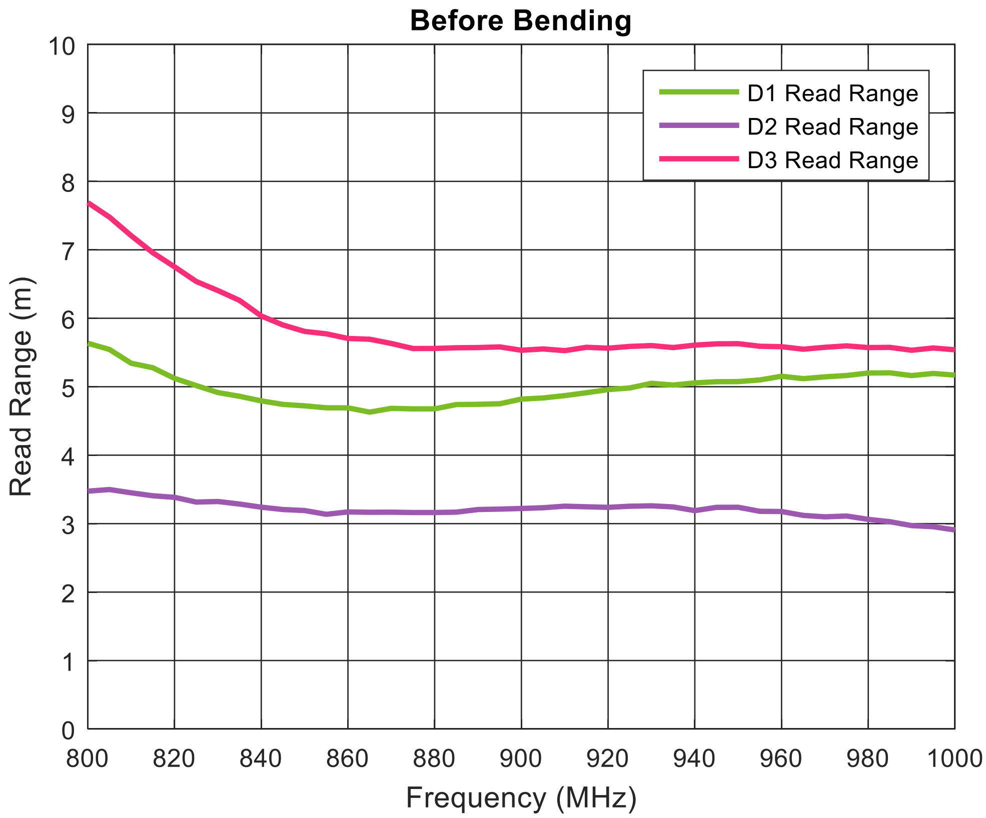

Figure 7-5 D Type Layered Tags

The figure 7-5 shows graph. The performance of D2 tag has decreased significantly, the read range has been dropped from 6 m to 3.5 m and it remained constant throughout the frequency band. The read range of other two tags remained almost same so it can be said that while making a layer on the antenna of tag the structure of antenna has been effected so the read range has decreased.

The behavior of tag D2 is almost constant throughout the frequency band of testing range which is exceptional as compare to the earlier results and for this one as well because other two tags D1 and D3 are showing a decreasing behavior in graph for the frequency range of 800-860 MHz and it’s constant for the operating frequency of UHF tags which is 860-960 MHz. From 960-1000 MHz the behavior is constant as well. The read range of D1 and D3 tag in the operating frequency range of UHF tags is between 5 to 5.5 m which is really convincing for the results.

7.2.8 Bending at (6.3 cm) Radius

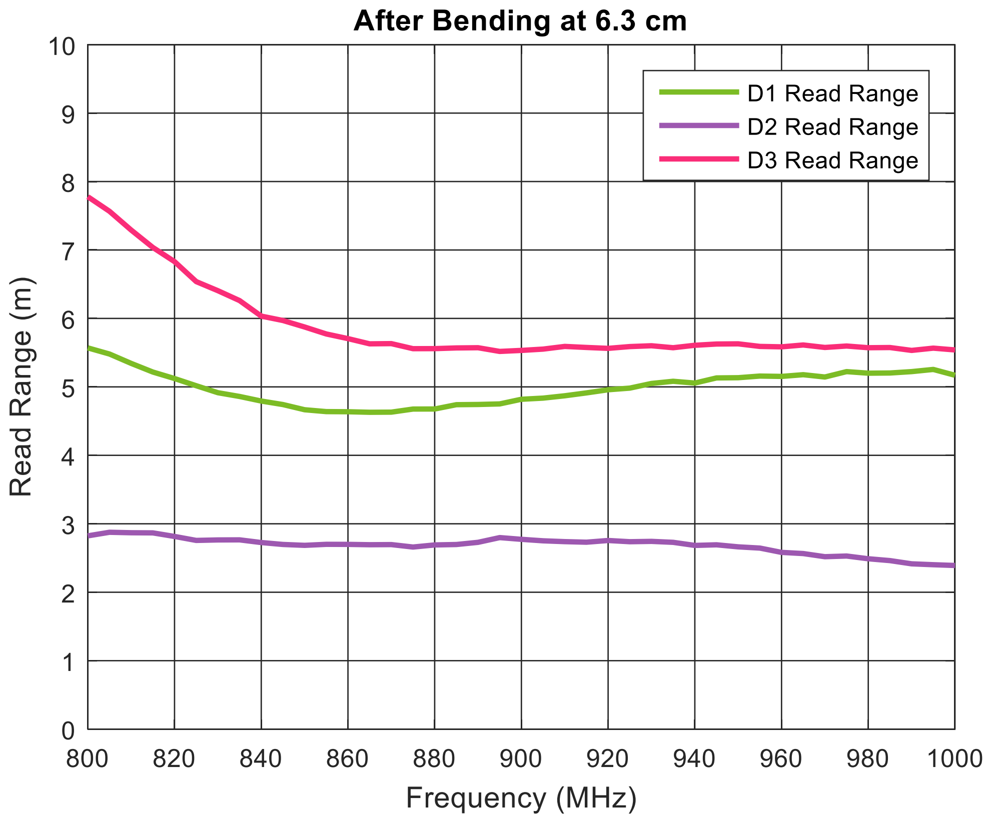

Figure 7-6 D Type Layered Tags after Bending

The figure 7-6 shows graph. The read range of D1 and D3 has a decreasing behavior in frequency range of 800-860 MHz which is then constant in the frequency range of 860-960 MHz and further extends to the 1000 MHz. The read range in the desired frequency range is between 5 to 5.5 m after bending the tags at a radius of 6.3 cm.

While the tag D2 has a constant read range throughout the frequency range of 800-1000 MHz. The read range is around 3 m for D2 tag and the reason for it is clear that tag has been damaged while bending at the radius of 6.3 cm. The other reason could be the change in structure of antenna or IC which is fixed with fixers.

But it can be concluded that all of the tags have almost same behavior in term of read range for the proposed frequency range after bending at the radius of 6.3 cm so it can be said that tags have performed well after bending as well and showing the results as similar to the results of tag before bending.

7.2.9 Bending at (5 cm) Radius

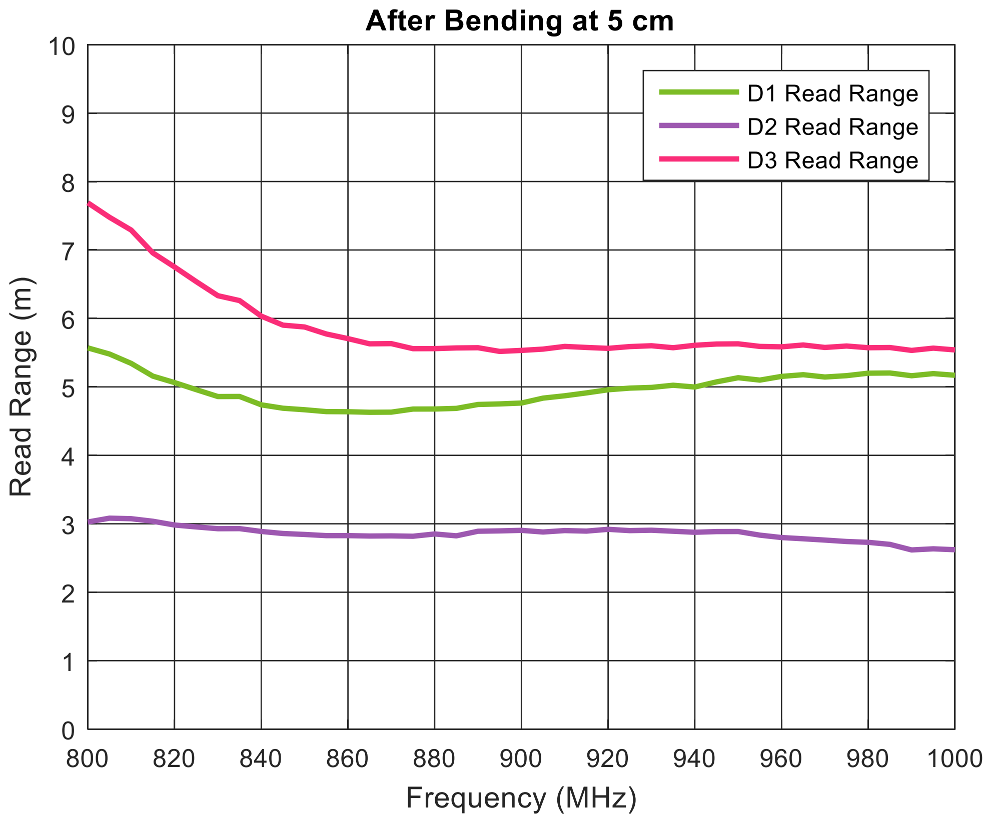

Figure 7-7 D Type Layered Tags after Bending

The figure 7-7 shows graph. The read range of D1 and D3 tags is decreasing in the frequency range of 800-860 MHz which is initially 5.5 m and 7.8 m and decreases to 4.9 m and 5.5 m respectively for D1 and D3 tags. In the frequency range of 860-960 MHz the read range for D1 and D3 tag is 5 m and 5.5 m respectively. The read range is almost constant in this frequency range while it is also constant in the frequency range of 960-1000 MHz.

D2 tag is having read range of 3 m which is constant throughout the frequency range of 800-1000 MHz. Which is same as before and it sees a bit increase in read range. So even after bending at 5 cm of radius there isn't any change in behavior of tag D2. The same statement is for the tags D1 and D3 which are having almost same behavior as of the results of read range for the tags D1 and D3 after bending at 6.3 cm.

So it can be concluded from the graph that all of the tags are having same behavior after bending at the radius of 5 cm. The tags have reasonably sustained its functioning while in bending reliability test for the radius of 5 cm. Tag D2 is only showing strange behavior throughout the testing. D1 and D3 have almost same read ranges. There isn't any impact of bending on D1 and D3 tags.

7.2.10 Bending at (3.7 cm) Radius

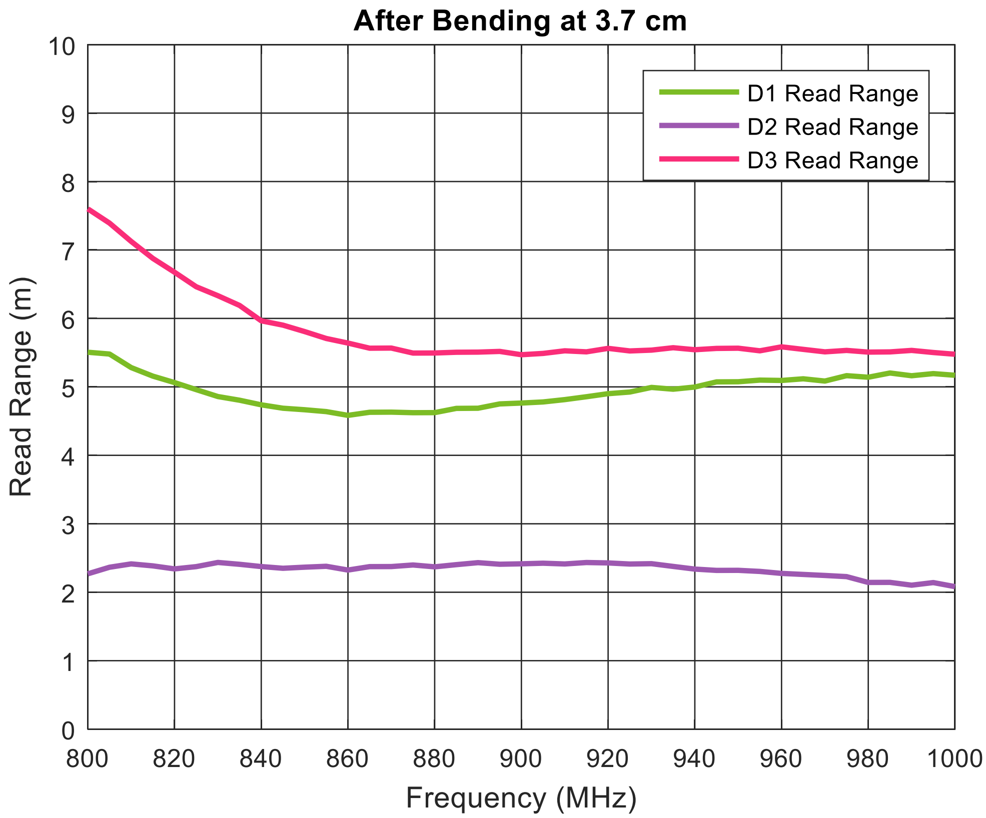

Figure 7-8 D Type Layered Tags after Bending

The figure 7-8 explains graph. The performance of tag D2 has been more affected after bending so the read range has decreased to almost 2.2 m but it remained almost constant in whole frequency band. The other two tags have almost same read ranges. All of the tags have almost same behavior as of the earlier readings taken. So it is concluded that there is very small impact of bending on the tags even after having a layer on the tags.

7.2.11 Bending Test

The water reliability of tags have been checked out by creating two cases. After bending the tags and passing them through three stages of bending, some of the layered tags showed cracks and those were noted down and again a layer was made to make them water proof and take the measurements in water.

7.2.12 Case 1

The tag has been immediately taken out from water and read range is measured. The desired water reliability test is to check the functionality of tags in water. In this test tags are placed in water and is taken out from water immediately. A bowl is filled with water and all the tags are placed in water separately are taken out simultaneously and placed in the chamber for measurements.

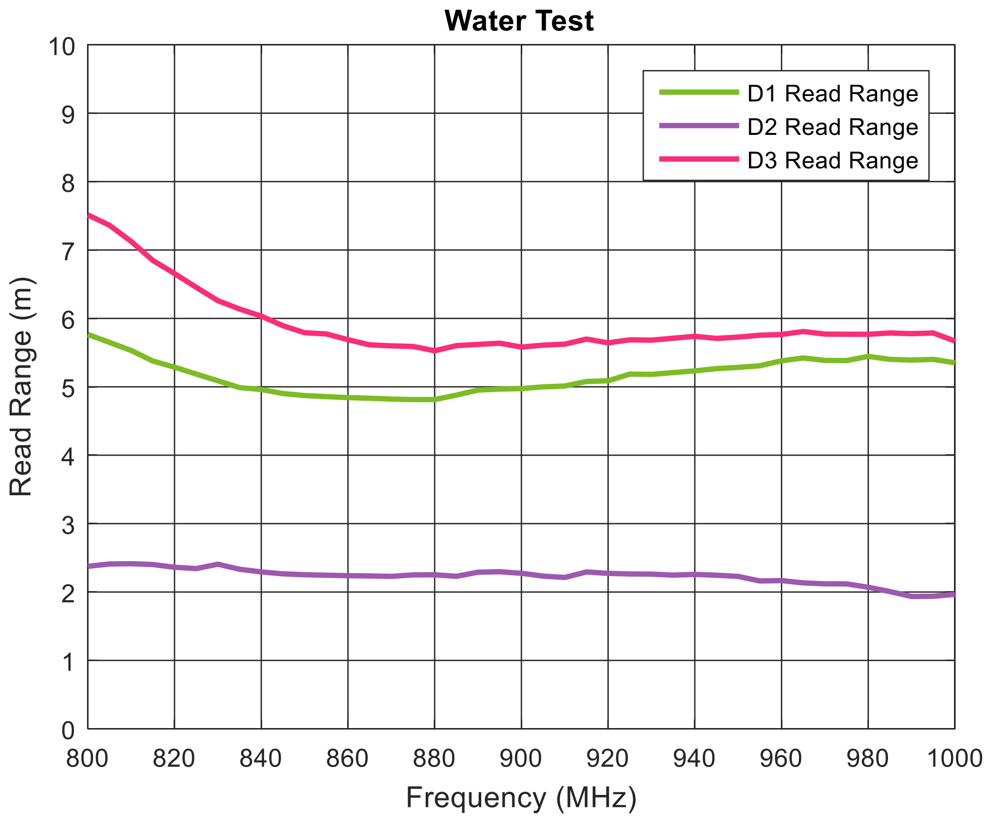

Figure 7-9 Water Reliability Test of D Type

The figure 7-9 above shows graph. There is a bit decrease in the read range of D3 but it is not that much while D2 has a decrease in read range from 3 m to 2.2 m which is constant in whole frequency band. The read range of the tags D1 and D3 is decreasing in the frequency range of 800-860 MHz and in the frequency range of 860-960 MHz it is almost constant and remains constant in the frequency range of 960-1000 MHz.

The read range in the operating frequency of UHF tags is around 5.5 m for both tags. The tags don't show any notable difference in read ranges except tag D2 so water has almost no impact in this case. It is concluded that all the tags have shown excellent results for the read ranges after being testing them in water for the water reliability test. So after this case of testing tags can be used in water environment.

7.2.13 Case 2

The tags are now kept in water for 3 minute and then taken out for the measurements of read range. The test is taken out the same way it has been done in case 1. The tags are placed in water for 3 minute in the same bowl and each tag is placed separately in water and after taking out from the water the tag is immediately placed in the chamber and read range of the tags are measured.

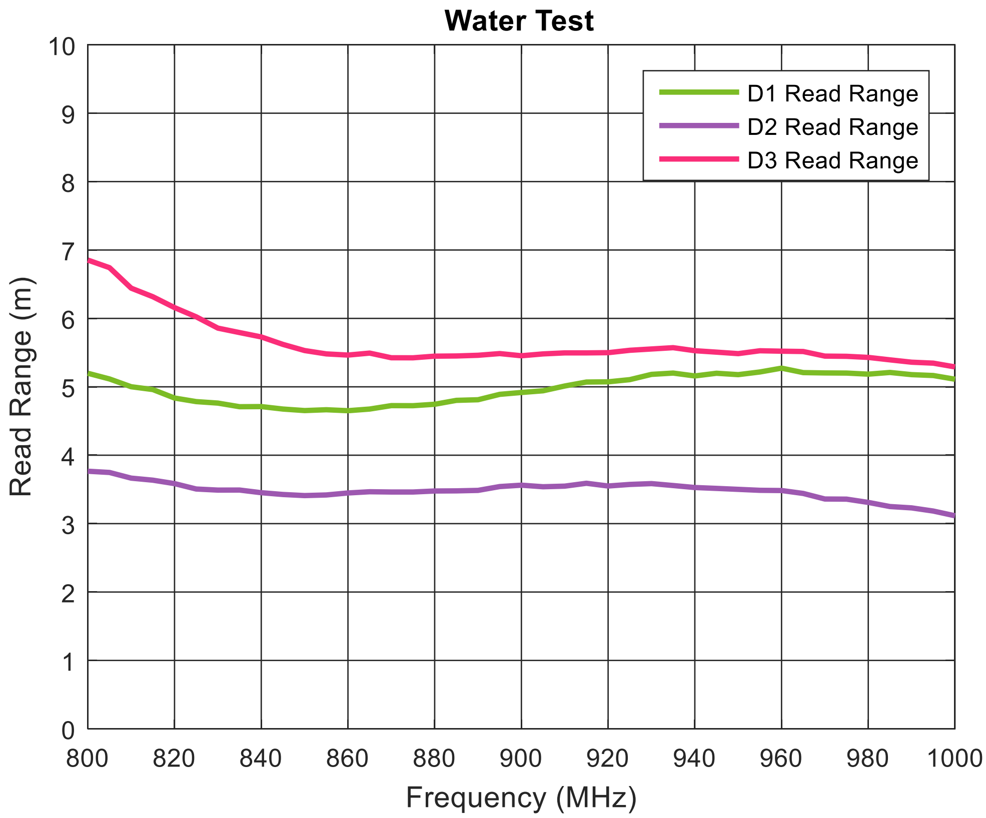

Figure 7-10 Water Reliability Test of D Type

The figure 7-10 explains graph. The read ranges of tag D1 is decreased from 5.8 m to 5.1 m and D3 from 7.5 m to 6.9 m while the read range of tag D2 is increased from 2.2 m to 3.8 m. As tags are water proofed but there was some water on the substrate so that is a reason that read ranges have bit decreased but it can be ignored so it can be said that read ranges of tags almost remained same except the tag D2 which is showing a strange behavior that read range has increased.

7.2.14 Dry Test

After getting the results of tags through water test the tags were placed on the table to be dried for 24 hours and then the measurements were taken again. The purpose of this test is to check either the difference in read ranges which occurs due to the water will fade away after drying or not.

Because for comparison of the values this test must be carried out after having the water reliability test. The tags are dried in an open environment and placed on the table for 24 hours and after that all the tags are place in chamber separately to have the readings of the read ranges of all the tested and dried tags.

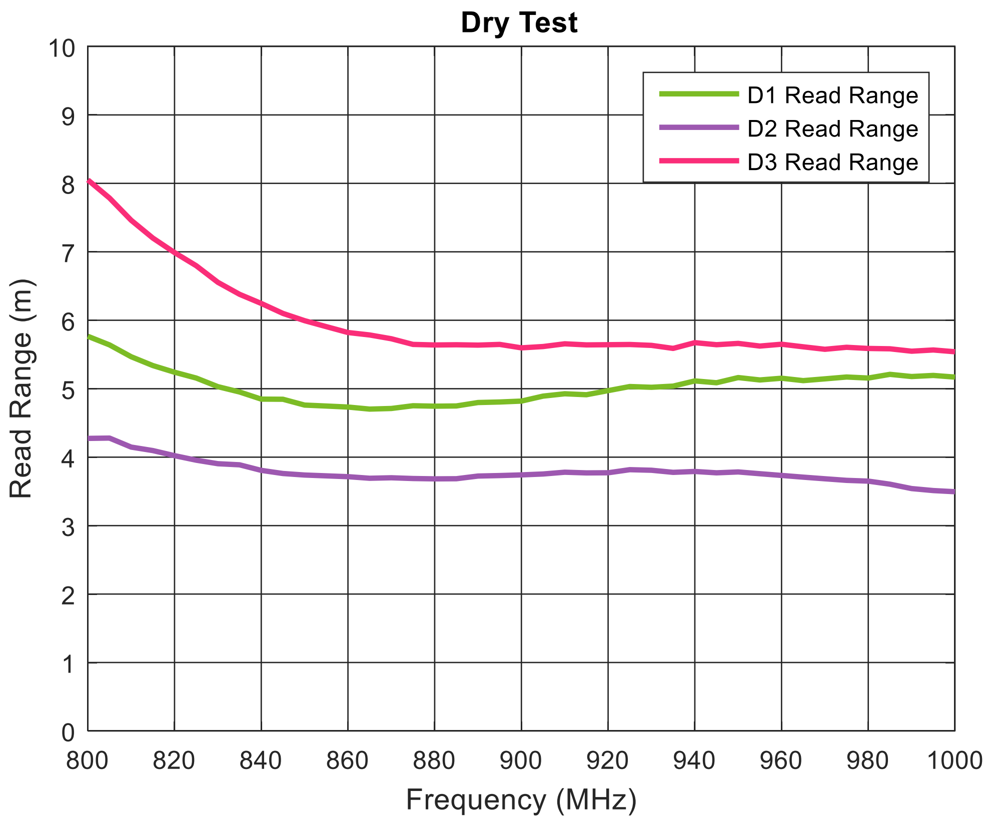

Figure 7-11 D Type Tags after Dry Test

Results can be seen in figure 7-11. After drying the read ranges of tags have almost gained the initial values as of the readings taken before the water test. The read ranges of tags D1 and D3 have a decreasing behavior in the frequency range of 800-860 MHz and in the frequency range of 860-960 MHz the read range almost remains constant and it has also same behavior in the frequency range of 960-1000 MHz.

Tag D2 is having almost same behavior throughout the testing. It has a read range of 4 m which is constant in the frequency range of 800-1000 MHz. So showing strange and different behavior as compared to the tags D1 and D3. But I is concluded that tags are having read ranges and behaviors as of the tags which are tested in water and after drying. So tags can be used in both reliability cases and the performance wouldn't be affected after these tests.

7.3 Type 'E' Tags

The results of E type tags are taken and a detail analysis is covered here for all type of reliability tests. This type of tag is different as compared to the D type tag. The difference of tags is based on the shape of substrates or platforms which are manufactured with 3D printing pen.

Three samples are manufactured with this shape of substrate and all the tests will be performed on this type of tag as of the D type tag has went through testing. Because we want to have a comparison of the tags on the basis of shapes and then compare the performance of both tags.

7.3.1 Before Bending

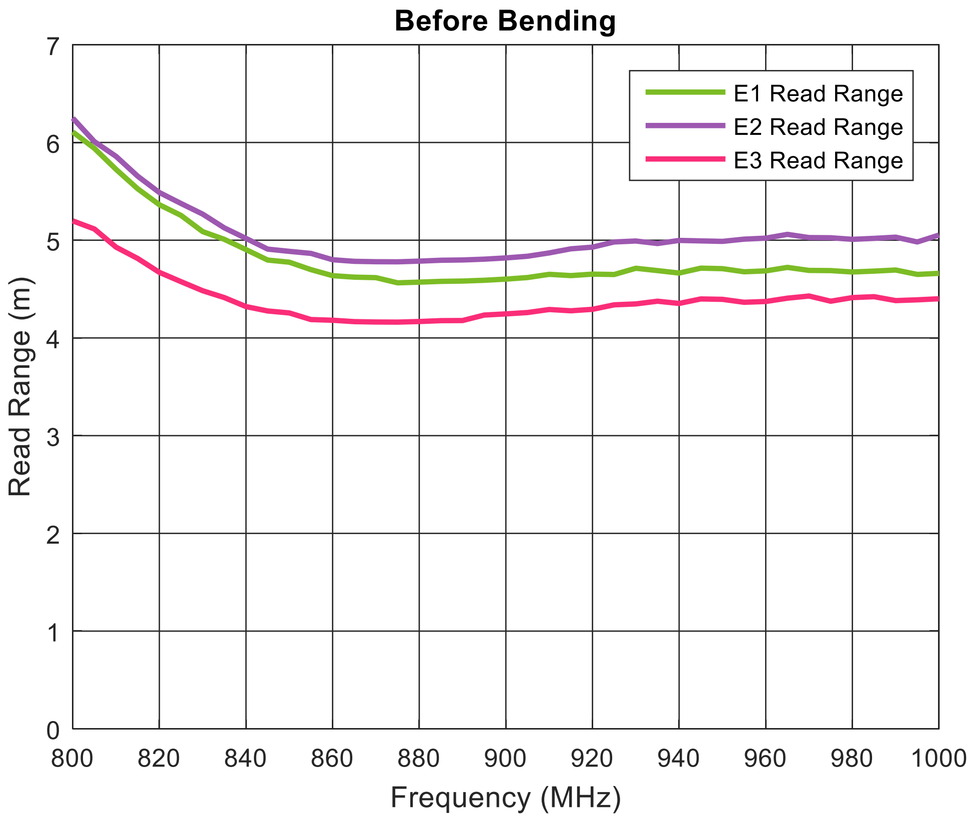

Figure 7-12 E Type before Bending

The figure 7-12 shows graph. E1, E2 and E3 have read ranges 6.1 m, 6.2 m and 5.2 m respectively. All tags have a decreasing trend in a frequency range of (800-860) MHz and in the frequency range of (860-1000) MHz the read ranges are almost constant. The final reading of read ranges at 1000 MHz of E1, E2 and E3 are 5 m, 4.7 m and 4.5 m respectively.

It can be observed that all the tags have same behavior in term of read range throughout the frequency band of testing. While in the desired frequency range for UHF tags which is 860-960 MHz the behavior of tags almost remains constant which is a positive sign in term of our usage for the tags.

7.3.2 After Bending

There were again three scenarios created for bending and radius of bending material was kept for 3.7 cm, 5 cm and 6.3 cm respectively so we have three readings for each type. For this purpose three samples of this type of tags are bended for three minutes and after that each tag is placed in chamber for the measurement purpose.

The purpose of bending is to check out the reliability of these tags in different bending situations that how well these tags perform in such environments so better applications can be allocated for the practical implementation purpose. The minimum radius for bending is kept 3.7 cm which is similar to the bending of any thing around wrist so these graphs will give us in depth understanding either our desired goal will be achieved or not.

7.3.3 Bending at (6.3 cm) Radius

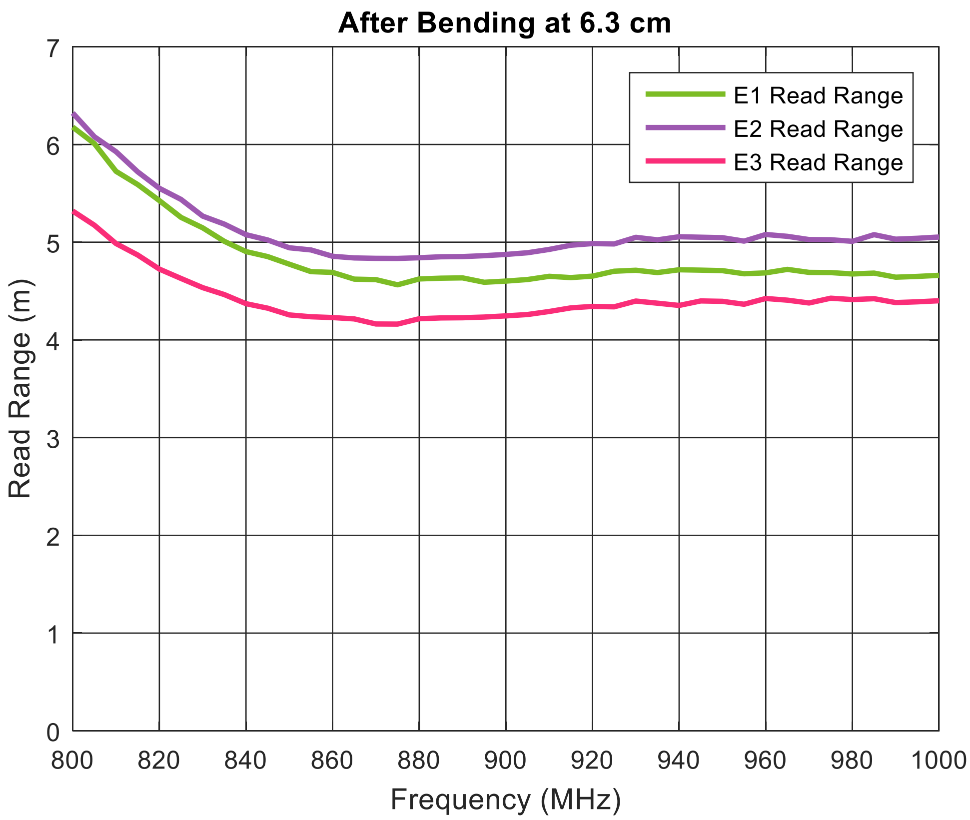

Figure 7-13 E Type after Bending

The figure 7-13 shows graph. The tags have a decreasing behavior in graph in the frequency range of 800-860 MHz and then read range is showing constant behavior in frequency range of 860-1000 MHz. There is only small difference in read range of these tags. E1, E2 and E3 has a read range around 4.8 m, 5 m and 4.5 m respectively.

The best thing about above graph is that no significant effect on the tags while bending in this scenario. So bending the tags at a radius of 6.3 cm has not shown any difference in read range. All the samples have almost same behavior of read ranges as of before bending, from graph it is clear that there isn't any noticeable difference in read range. The bending at this radius have no effect on the performance of tag, while the tags were in whatever shape and condition.

7.3.4 Bending at (5 cm) Radius

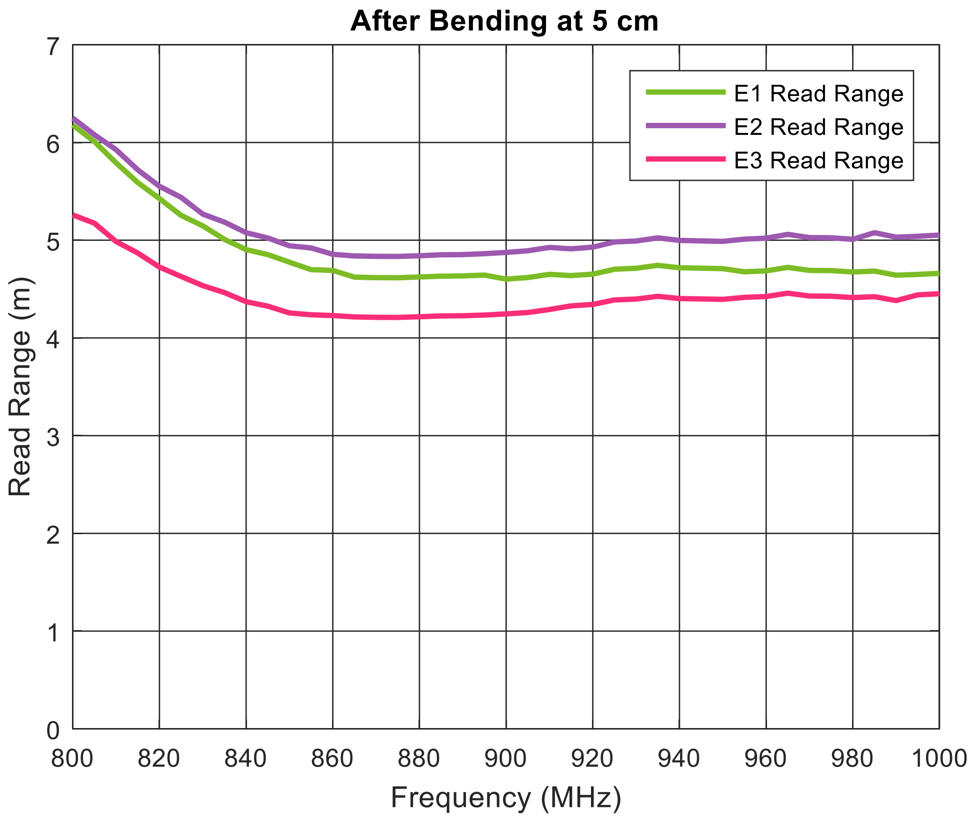

Figure 7-14 E Type after Bending

The figure 7-14 shows graph. In this case the tags are bended at a radius of 5 cm of thermago for three minutes and then these tags are measured and graph represents the results of measurements.

The read range for all the tags have a decreasing trend in the frequency range of 800-860 MHz which has decreased from 6.2 m to around 5 m for E1 and E2 while in case of E3 the read range has decreased from 5.2 m to 4.2 m and these read ranges then remain constant in frequency range of 860-1000 MHz.

Read ranges remained same in this case as well. Same is the situation with this case that tags have performed very well and sustained the bending at radius of 5 cm. It can be said that tags are in ideal situation and bending has no impact on the tags. It is concluded that graph represents tags have sustained the bending and there isn't any significant effect on the performance of tags due to bending and these tags can be used in a bending scenario where the radius of application is around 5 cm.

7.3.5 Bending at (3.7 cm) Radius

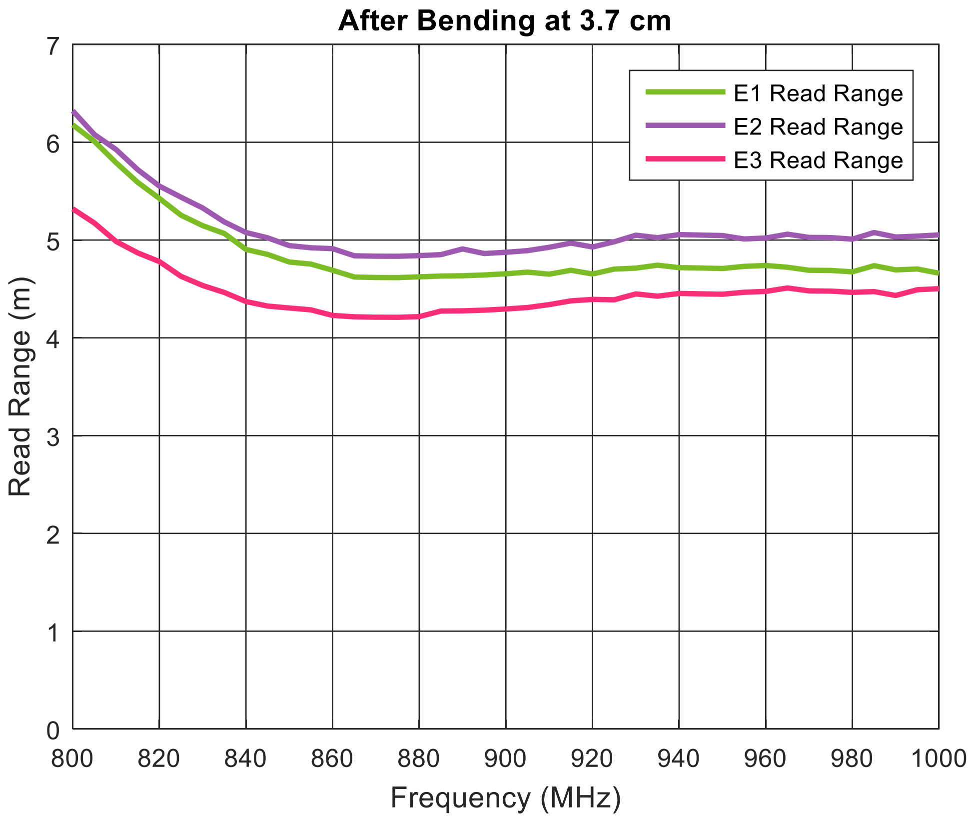

Figure 7-15 E Type after Bending

The figure 7-15 shows graph. The graph is identical to the previous graph for the tags. The read range of tags E1, E2 and E3 has decreasing behavior in frequency range of 800-860 MHz and in the frequency range of 860-1000 MHz the read range remains constant throughout the mentioned range of frequency band. It is obvious from the graph that read range is around an average of 5.5 m for all the tags at a bending situation of 3.7 cm.

Read ranges of tags are almost same as of the initial readings taken without bending. So there isn't any impact of bending on the tags. It can be concluded that read range is not effected due to bending at such a small radius and tags remained in original shape. Which is convincing finding for the applications to be used at such a small radius and that can be any wearable application which has a size of wrist to be implemented.

7.3.6 Layered Tags

Then a layer is made on the conductive thread of antenna and IC as well and those were well water proofed. The layer 3D printed on the antenna and IC with 3D pen and same material has been used for printing the layer which is used for manufacturing the substrates. Layers are printed carefully that antenna structure and IC may not get effected while in bending scenarios and during water reliability test as well because these tags will now be tested for both reliabilities and performance of tags will lead to make the decisions either tags can be used in such situations or not. These tags will be measured before bending as well so better comparison of the tags can be presented.

7.3.7 Before Bending

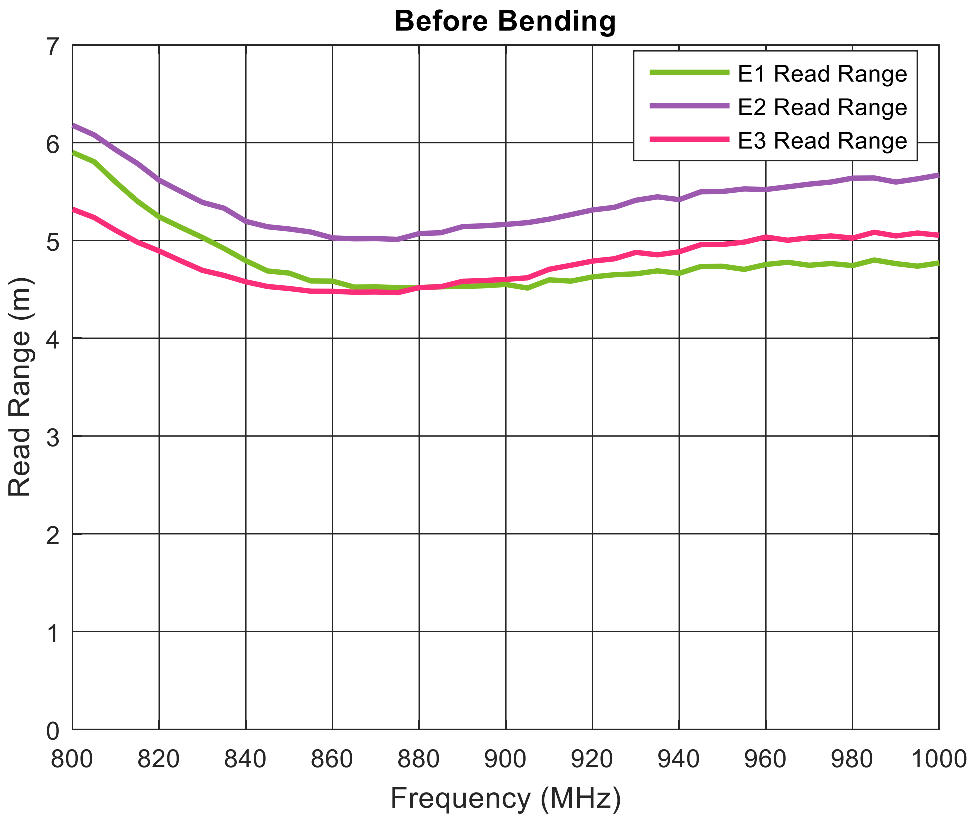

Figure 7-16 E Type before Bending

The figure 7-16 shows graph. The read range of E1 is decreased a little bit but seeing a same behavior as before. The read range of tag E2 has seen a little decrease at initial value, it has a decreasing trend in the band of (800-860) MHz while in the band of (860-1000) MHz it has an increasing behavior which is constant in previous case.

The final reading is 5.7 m which was 5 m in previous case. The read range of E3 at initial frequency is same as before and has decreasing trend in (800-860) MHz while in (860-1000) MHz it has an increasing behavior. The read range at final frequency 1000 MHz is 5 m which is 4.5 m in previous case. So E1 and E3 is seeing an increasing trend in read range. While E2 is almost same.

7.3.8 Bending at (6.3 cm) Radius

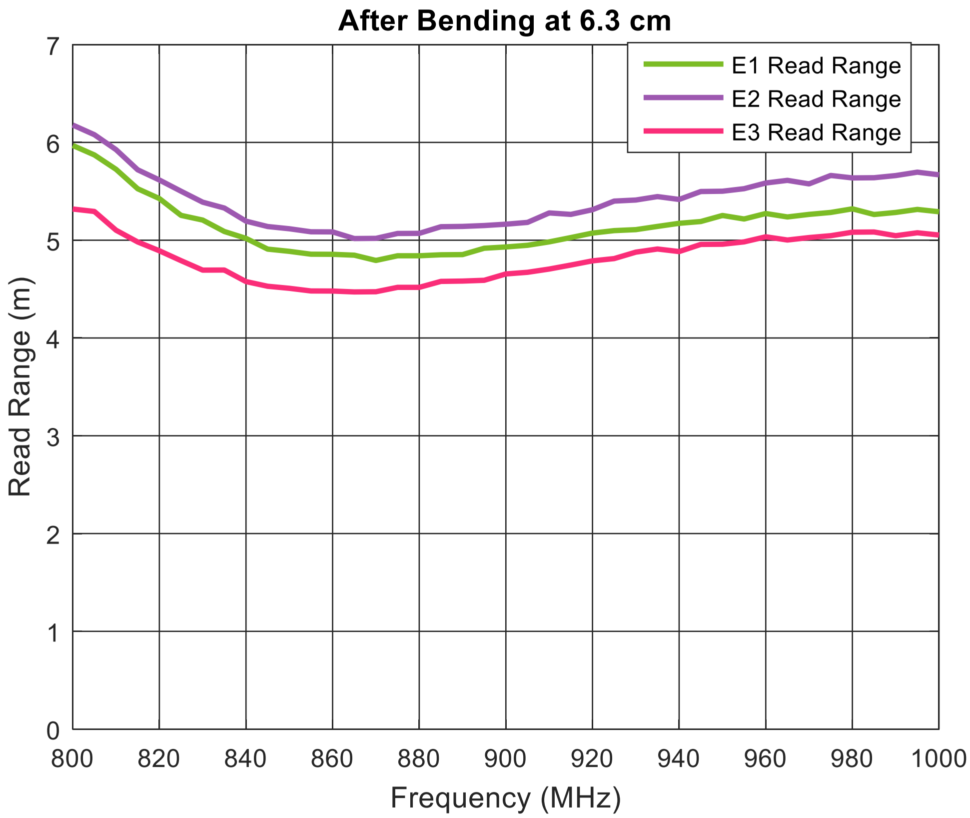

Figure 7-17 E Type Layered Tags after Bending

The figure 7-17 shows graph. The bending situation is now at a radius of 6.3 cm for the tags with layer printed on the antenna and IC so there was a possibility that while in bending and due to the layer the tags might show some changes in behavior but as graph shows that read range in the frequency band of 800-860 MHz has a decreasing behavior and is then increasing in the frequency range of 860-1000 MHz but this increase is not that much significant which can be ignored and the behavior is considered almost constant in this range.

It can be analyzed from the graph that, there isn't such difference in read ranges after bending in this situation. These tags are constantly showing excellent results and performing like there is no impact of bending on the tags. Even the layer has not affected the performance of tags. It can be concluded that bending the tags at a radius of 6.3 cm and layer on the tags has not affected the performance of tags.

These tags can be used in a situation where the bending situation has a radius of around 6.3 cm and layer can also be printed so both these tests have given us the finding that we can proceed further with these tags for remaining bending situations and can compare our findings and results.

7.3.9 Bending at (5 cm) Radius

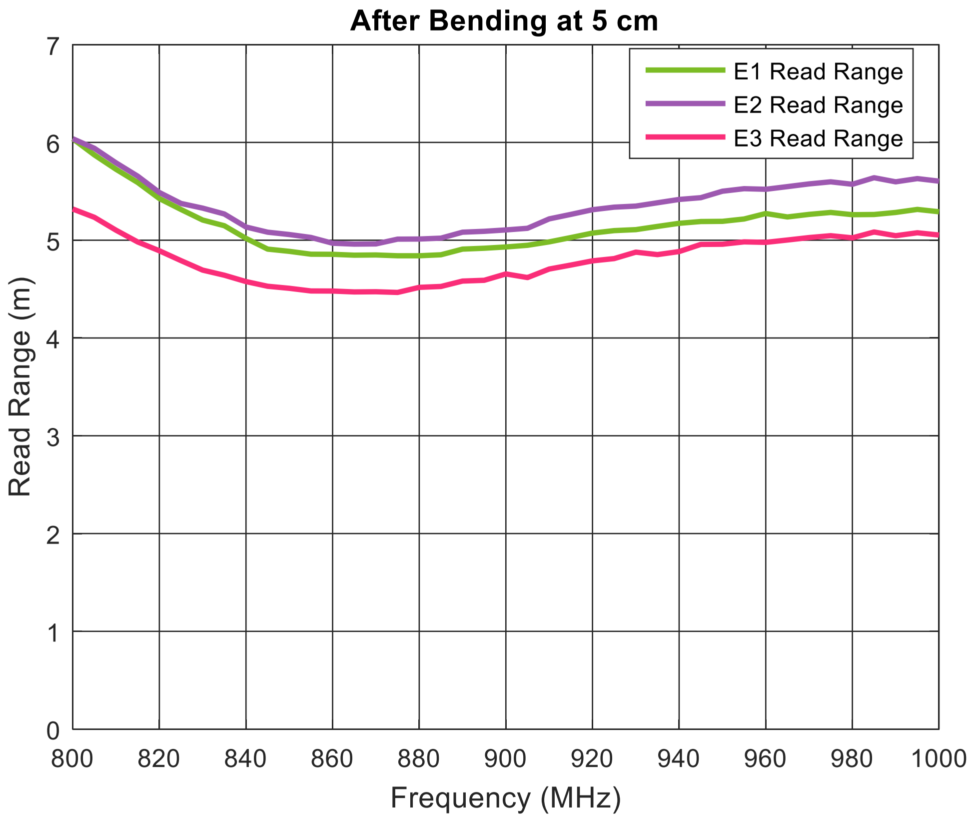

Figure 7-18 E Type Layered Tags after Bending

The figure 7-18 shows graph. The read range of the tags is decreasing in frequency range of 800-860 MHz and then it has an increasing behavior in the frequency range of 860-1000 MHz. But this increase in read range is not that much so it is ignored and read range in the operating frequency of 860-960 MHz is almost constant which is enough to make the decision that bending at a radius of 5 cm for the tags has not any impact and performance of tags has remained same as of before.

All the tags are showing almost same behavior as of the previous case. Even it is bended more than 6.3 cm but the effect of bending doesn't change and tags are showing normal results. As the bending radius has been decreased and it was anticipated that tags will show some significant change in the performance and would affect the results of read range but graph has a very clear result that tags can be used in a bending situation where the radius of bending is around 5 cm and these tags can be taken for further testing of bending as the layer on the tag has remained unaffected and no changes in the shape of tags are observed.

7.3.10 Bending at (3.7 cm) Radius

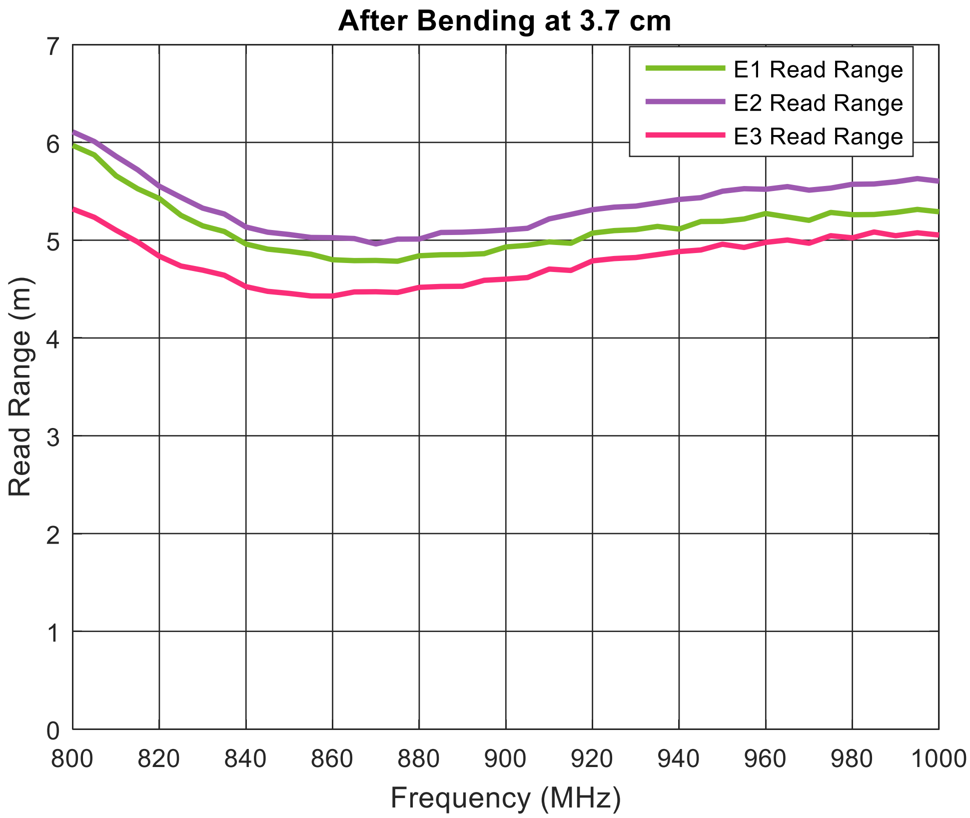

Figure 7-19 E Type Layered Tags after Bending

The figure 7-19 shows graph. E2 is also showing the same behavior as of the tags E1 and E3 has shown in case of without bending. So it is analyzed here that in band of frequency (800-860) MHz tags have decreasing trend of read range while in band of (860-1000) MHz the trend is increasing. So it can be said that tags have almost same behavior or trend in terms of read range readings in these cases of bending. Bending radius is identical to the wrist of any normal person so these tags can perform well while using them in a situation of wrist and wearable applications.

7.3.11 Water Test

After bending the tags and passing them through three stages of bending, some of the layered tags showed cracks and those were noted down and again a layer was made to make them water proof and take the measurements in water. There were two scenarios used to check the results of tags in water.

7.3.12 Case 1

The tags are placed in water and are taken out immediately from water to check out the results. The layer has been printed on the antenna and IC so the water has not effect on the performance of tags and better results can be achieved while in a situation of water reliability test. In this case tags are placed in bowl of water and are taken out immediately and placed in the chamber for measurements. Each tag is measured and tested separately.

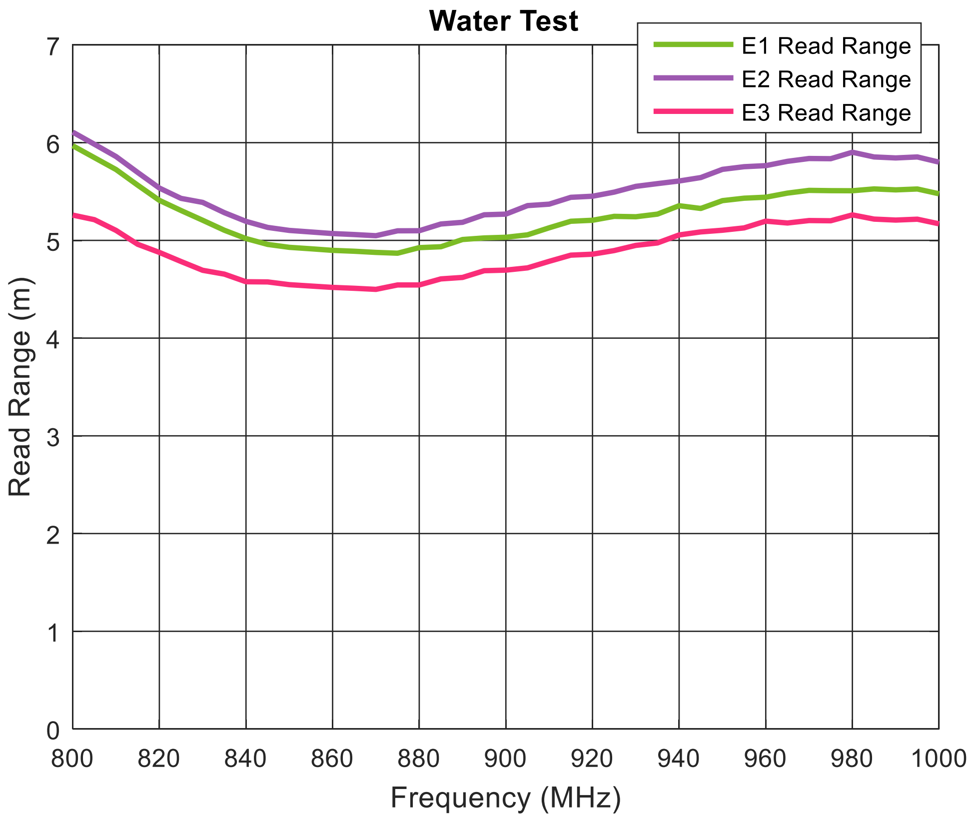

Figure 7-20 Water Reliability Test of E Type

The figure 7-20 shows graph. The read range of the tags has a decreasing behavior in the frequency range of 800-860 MHz and in the frequency range of 860-1000 MHz the read range has an increasing impact but it is not that much significant so it can be ignored. Due to water this could have affected the reading a little bit.

Tags have experienced almost no difference at initial values but at final frequency it can be said that read range has bit increased for all the tags. But tags have almost same behavior in overall.

7.3.13 Case 2

The tags are now placed in water for 3 minute and then taken out from water and measurements for read ranges are taken. This test has also been performed separately for each tag and tags are placed in water for 3 minute and then are taken out from water and are directly carried in the chamber for measurements.

This test is performed to check out the better water reliability of tags that how well it can perform if it is placed for a longer period in water because situations vary application to application and the usage of the application changes person to person.

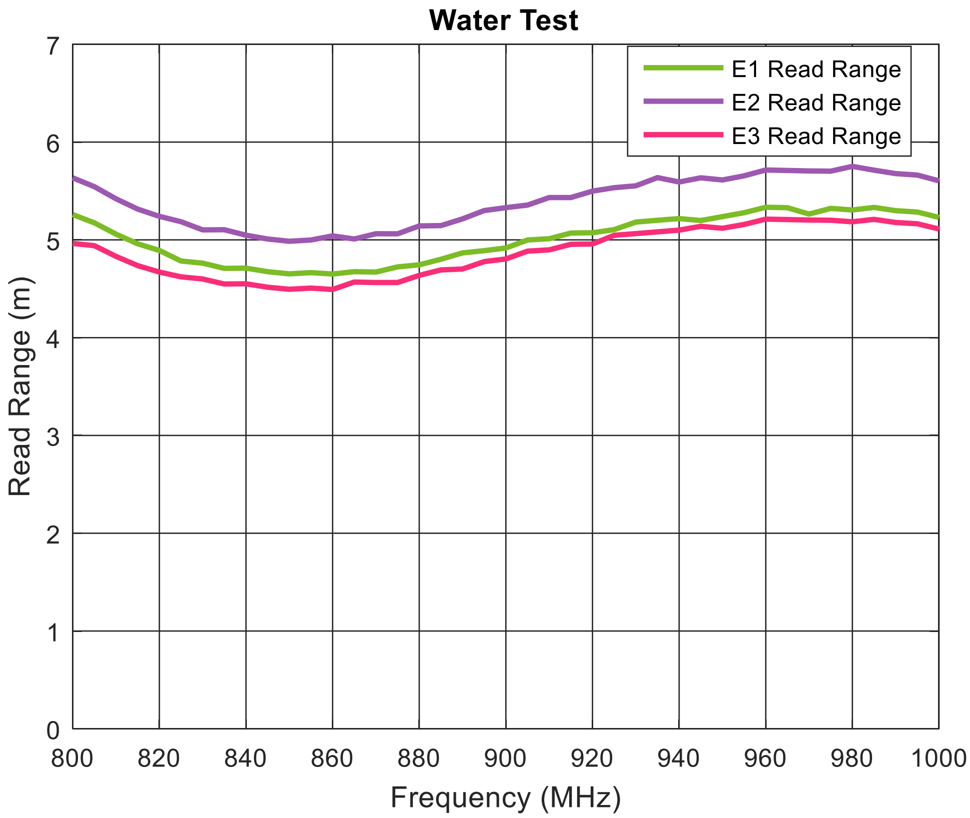

Figure 7-21 Water Reliability Test of E Type

The figure 7-21 shows graph. The initial reading of read range has decreased almost 2 m for each tag while the final reading is almost same but the behavior of read range of all the tags remains almost same to the reading of previous case. That is impact of water which was there on the substrate although it didn’t had any intact with antenna.

7.3.14 Dry Test

After getting the results of tags through water test the tags were placed on the table to be dried for 24 hours and then again the measurements were taken. This test has been performed to compare the results and findings for the tags that how these tags performed before water reliability and then in water reliability test, after drying if some changes have occurred in the process of water reliability test either these tags have gained back the performance after drying or not. So these tags are placed on the table in open air and tested after 24 hours so the water may dry out properly and better results can be achieved which will lead to the better analysis and comparison.

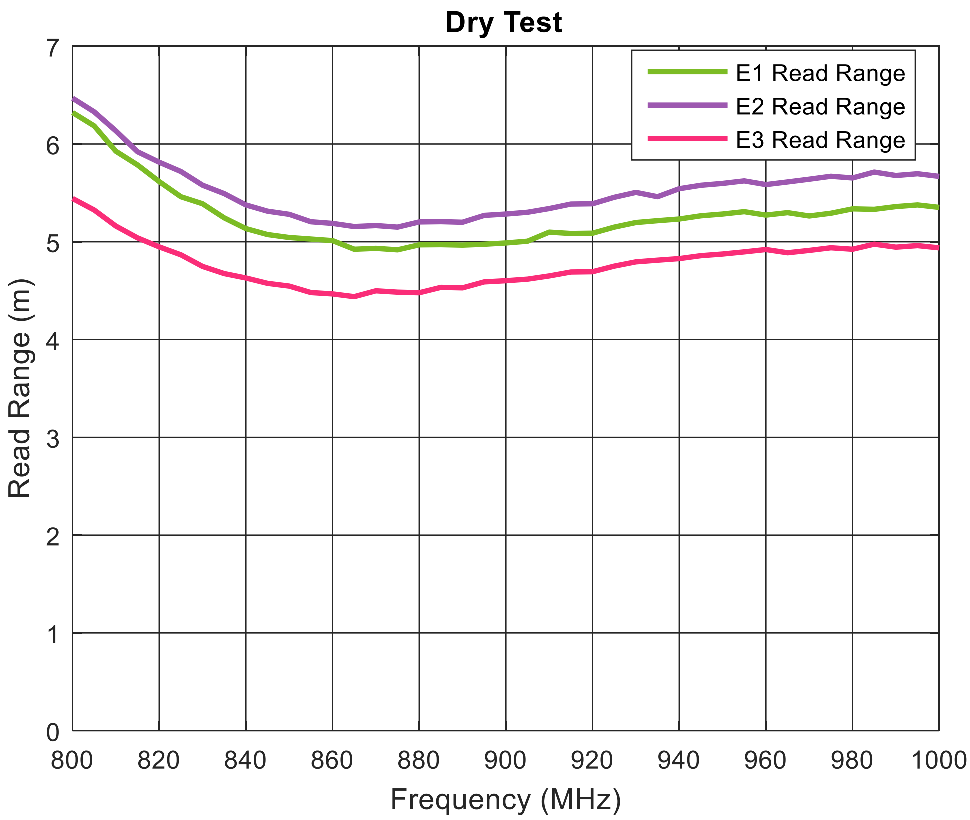

Figure 7-22 Dry Test of E Type

The figure 7-22 shows graph. The tags have gained back the read ranges as of the case before tags were put in the water. So the 2 m of loss in read range has been gained back after drying. This test has proved the point that whatever the effect water had produced on the performance of tags has now been achieved back after drying. So concluded that tags have no significant changes in performance after being tested in all situation.

7.4 Comparison of Tags

The tags of D and E type have performed well in all reliability tests, but E type tags have shown more reliable results as compared to the D type. Because one of the sample of D type tag had wide variations in readings of read range and it is due to the manufacturing fault or the bending has changed the structure and IC is displaced. E type tags are reliable and can be taken for further study.

8. APPLICATIONS AND FUTURE WORK

There is wide range of applications of RFID which almost touches every technology. It can be used in various wearable technologies, one of the application can be temperature sensing with RFID at some distance [40]. This tag can be used for packaging system technology [41]. As the main aim of the thesis was to have bending reliability which has been achieved so these tags can now be used in bending environments like arms and legs etc. It is easy to carry the equipment of manufacturing anywhere so astronauts can carry it to the space and manufacture the tags easily according to the situation needed and implement. There is wide range of applications like retails, energy sector and automobiles, it highly depends on one's interest and ease of use. The applications can be extended in any field of technology according to the requirements and needs of the subject because enough bending and water reliability has been achieved so there wouldn't be any limitation of usage of the tag. We can easily carry this tag in water as the functionality isn't disturbed due to the water.

For future work one of the application should be of great help that temperature sensing can be done remotely with tag and this research has already been done that temperature sensing at a distance of 2.5 m is done so we have received a read range of 6 m at least, this material type can be used to make a sensor tag for temperature sensing and results can be compared. The conductive glue has been removed in this manufactured tag so these 3D printed fasteners should be tried in other materials as well to embed the IC on antenna because it is cheap and time efficient. In this thesis only bending and water reliability is checked so other reliability tests should also be performed as a further research and better understanding of the material. An already simulated antenna has been used for the manufacturing of antenna in this tag but simulations haven't been performed with the properties of this material so for better comparison in simulated results and manufactured tag's results the simulation should be performed with the substrate material's properties in HFSS.

This tag has been aimed for wearable applications so testing the tags on human body can be done as a further research and study of implementation in real environment will be helpful for deep understanding. The compatibility factor should be increased which can be done through HFSS simulation of antenna. The conductive thread has been used for antenna manufacturing so an alternate of this thread can be found in form of conductive material for 3D printing pen and use that to print the antenna because thread can be fragile and broke down easily although we have used four time of the thread originally needed to make the antenna more reliable. It is also planned that now a research paper will be published on the basis of findings of this thesis.

9. CONCLUSION

The objectives of this thesis which were set before starting the thesis have been achieved well according to desire. The conductive glue has been successfully replaced by BPA free material's 3D printed fasteners so enough of time efficiency has been attained because these fasteners dry out in minutes and conductive glue takes hours to dry out. Through this experiment the time of testing the manufactured tag has been reduced a lot. The feasibility of tags has been tested in bending and water and the results are promising so it is concluded that this material can be used in water and bending environment because the results of read range almost remained same. This material and equipment used is really cheap and easy to handle which is relieving as every field looking towards cheaper and reliable products. The material used is eco-friendly. The read range of both type of tags have almost remained close to the 6 m which is considered as really excellent read range for many applications [42]. This read range remains almost same in all reliability tests. It is concluded that all the objectives of this thesis have been achieved quite efficiently with real and reliable results.

10. REFERENCES

[1] I. Gibson, D. W. Rosen and B. Stucker, Additive Manufacturing Technologies, New York: Springer Science+Business Media, LLC, 2010.

[2] J. Thrasher, "RFID Insider," 2013. [Online]. Available: https://blog.atlasrfidstore.com/3d-printing-rfid-innovate-life.

[3] L. Bolotnyy and G. Robins, "Multi-Tag RFID Systems," in *International Conference on Wireless Algorithms, Systems and Applications*, Chicago, 2007.

[4] X. Chen, L. Ukkonen and J. Virkki, "Reliability Evaluation of Wearable Radiofrequency Identification Tags: Design and Fabrication of a Twopart Textile Antenna," *Textile Research Journal,* vol. DOI, 2018.

[5] Y. Xu, X. Wu, X. Guo, B. Kong, M. Zhang, X. Qian, S. Mi and W. Sun, "The Boom in 3D-Printed Sensor Technology," *MDPI Sensors,* vol. 17, no. 5, p. 1166, 2017.

[6] M. C. Caccami and G. Marrocco, "Electromagnetic Characterisation of Self-Tuning UHF RFID Tags for Sensing Application," in *IEEE International Symposium on Antennas and Propagation (APSURSI)*, Fajardo, 2016.

[7] S. Taoufik, A. E. Oualkadi, F. Temcamani, B. Delacressonniere and P. Dherbécourt, "Simulation and Experimentation of an RFID System in the UHF Band for the Reliability of Passive Tags," in *Mediterranean Conference on Information & Communication Technologies*, Morocco, 2016.

[8] G. Marrocco, "The Art of UHF RFID Antenna Design: Impedance-Matching and Size-Reduction Techniques," *IEEE Antennas and Propagation Magazine,* vol. 50, no. 1, pp. 66-79, 2008.

[9] M. Roberti, "The History of RFID Technology," RFID Journal, 2005. [Online]. Available: www.rfidjournal.com.

[10] D. M. Dobkin, The RF in RFID, Oxford: Newnes, 2007.

[11] S. Dua, "RFID 4u," eSmart Source, Inc., 2017. [Online]. Available: https://rfid4u.com.

[12] K. Finkenzeller, RFID Handbook, Munich: John Wiley & Sons Ltd, 2010.

[13] L. Castro and S. F. Wamba, "An Inside Look at RFID Technology," *Journal of Technology Management and Innovation,* vol. 2, no. 1, pp. 128-141, 2007.

[14] "Symbol," Symbol, 2018. [Online]. Available: www.symbol.com.

[15] S. Xu, W. Li, S. Yi, C. Huang, C. Wu and H.-l. Chi, "Spatial Signal Attenuation Model of Active RFID Tags," in *ISPAN-FCST-ISCC*, Exeter, 2017.

[16] A. Buffi and P. Nepa, "An RFID-Based Technique for Train Localization with Passive Tags," in *IEEE International Conference on RFID (RFID)*, Phoenix, 2017.

[17] I. Poole, "Radio-Electronics," Radio-Electronics, 2018. [Online]. Available: www.radio-electronics.com.

[18] L. Wang and A. C. A, "Factors Affecting RFID System Performance and Non-parametric Analysis," *American Journal of Systems and Software,* vol. 4, no. 2, pp. 94-100, 2014.

[19] J. Virtanen, J. Virkki, L. Sydänheimo, M. Tentzeris and L. Ukkonen, "Automated Identification of Plywood Using Embedded Inkjet-Printed Passive UHF RFID Tags," *IEEE Transactions on Automation Science and Engineering,* vol. 10, no. 3, pp. 796-806, 2013.

[20] T. Wohlers, Rapid Prototyping & Tooling State of the Industry, Colorado: WOHLERS ASSOCIATES, INC, 2009.

[21] B. Redwood, "3D HUBS," 3D Hubs, 2018. [Online]. Available: www.3dhubs.com.

[22] T. Finnes, "High Definition 3D Printing – Comparing SLA and FDM Printing Technologies," *The Journal of Undergraduate Research,* vol. 13, no. 3, pp. 10-26, 2015.

[23] J. Pomell, A. Silvonen, N. Lagus, H. Kim, J. Partanen, P. Kiviluoma and P. Kuosmanen, "Adaptive Selective Laser Sintering Testing Device For Process Research in 3D Printing," in *International DAAAM Baltic Conference*, Tallinn, 2015.

[24] P. Pradel, Z. Zhu, R. Bibb and J. Moultrie, "Designing end-use Components for Additive Manufacturing," University of Cambridge, Cambridge, 2017.

[25] "3D Insider," 3D Insider, 2018. [Online]. Available: www.3dinsider.com.

[26] "3D EnginEarrings," 3D EnginEarrings, 2018. [Online]. Available: www.3denginearrings.com.

[27] R. Want, "An Introduction to RFID Technology," *IEEE Pervasive Computing,* vol. 5, no. 1, pp. 25-33, 2006.

[28] F. J. Valente and A. C. Neto, "Intelligent Steel Inventory Tracking with IOT / RFID," in *IEEE International Conference on RFID Technology & Application (RFID-TA)*, Warsaw, 2017.

[29] F. Calignano, "Overview on Additive Manufacturing Technologies," *Proc. IEEE,* vol. 105, no. 4, pp. 593-612, 2017.

[30] B. Sanz-Izquierdo and S. Jun, "WLAN Antenna on 3D Printed Bracelet and Wrist Phantom," in *Loughborough Antennas and Propagation Conference (LAPC)*, Loughborough, 2014.

[31] M. Rizwan, A. A. Kutty, M. Kgwadi, T. D. Drysdale, L. Ukkonen and J. Virkki, "Comparitive Study of Inkjet and Thermal Printing for Fabrication of Passive UHF RFID Tags," in *10th European Conference on Antennas and Propagation (EuCAP)*, Davos, 2016.

[32] J. D. Griffin, G. D. Durgin, A. Haldi and B. Kippelen, "RF Tag Antenna Performance on Various Materials Using Radio Link Budgets," *IEEE Antennas and Wireless Propagation Letters,* vol. 5, no. 1, pp. 247-250, 2006.

[33] H. Lehpamer, RFID Design Principles, Norwood: Artech House, 2012.

[34] D. Girbau, A. Lázaro and R. Villarino, "Passive Wireless Permittivity Sensor Based on Frequency-Coded Chipless RFID Tags," in *IEEE/MTT-S International Microwave Symposium Digest*, Montreal, 2012.

[35] M. Rizwan, M. W. A. Khan, L. Sydänheimo and L. Ukkonen, "Flexible and Stretchable 3D Printed Passive UHF RFID Tag," *IEEE Antennas and Wireless Propagation Letters,* vol. 53, no. 15, pp. 1054-1056, 2017.

[36] L. F. Lagunes-Aranda, A. G. Martinez-Lopez, J. Martinez-Castillo, C. M. Calderon-Aguirre, L. J. J. Morales-Mendoza and M. Gonzalez-Lee, "UHF RFID Antennas Integrated on Flexible Substrate for Health Care Environments," in *International Conference on Computing Systems and Telematics (ICCSAT)*, Xalapa, 2015.

[37] D. V. Thiel, "Stand on Standards," *IEEE Antennas and Propagation Magazine,* vol. 46, no. 1, pp. 120-121, 2004.

[38] X. Chen, L. Ukkonen and J. Virkki, "Reliability Evaluation of Wearable Radio Frequency Identification Tags: Design and Fabrication of Two-Part Textile Antenna," *Textile Research Journal,* vol. DOI, 2018.

[39] M. Rizwan, M. W. A. Khan, L. Sydänheimo, J. Virkki and J. Ukkonen, "Flexible and Stretchable Brush-Painted Wearable Antenna on a 3D Printed Substrate," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, no. 1, pp. 3108-3112, 2017.

[40] R. Colella and L. Catarinucci, "Application of the Pseudo-BAP mode to a 3D-Printed Wearable UHF RFID Tag with Sensing Capabilities," in *International Conference on Smart and Sustainable Technologies (SpliTech)*, Split, 2018.

[41] M. Hasani, L. Sydänheimo and L. Ukkonen, "Design and Implementation of Fully 3D Miniaturized Passive UHF RFID Tag for Sensing Applications," in *Loughborough Antennas & Propagation Conference (LAPC)*, Loughborough, 2015.

[42] M. Rizwan, M. Guibert, A. Massicart, J. Torres, L. Sydänheimo, L. Ukkonen, T. Björninen and J. Virkki, "Embroidered Passive UHF RFID Tag on Flexible 3D Printed Substrate," in *Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL)*, Singapore, 2017.