DESIGN OF A WIDEBAND WEARABLE U-SLOT ANTENNA WITH HEXAGONAL EBG GROUND FOR WLAN APPLICATIONS

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
MICROWAVE & OPTICAL COMMUNICATION

Submitted by:

DIVYANSHI VERMA
2K16/MOC/03

Under the supervision of

PROF. N. S. RAGHAVA

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

JULY, 2018

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, Divyanshi Verma, Roll No. 2K16/MOC/03 student of M.Tech. (MICROWAVE AND OPTICAL COMMUNICATION), hereby declare that the project Dissertation titled **"DESIGN OF A WIDEBAND WEARABLE U-SLOT ANTENNA WITH HEXAGONAL EBG GROUND FOR WLAN APPLICATIONS"** which is submitted by me to the Department of ELECTRONICS AND COMMUNICATION ENGINEERING, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

Place: Delhi **DIVYANSHI VERMA**

Date:

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the Project Dissertation titled **"DESIGN OF A WIDEBAND WEARABLE U-SLOT ANTENNA WITH HEXAGONAL EBG GROUND FOR WLAN APPLICATIONS"** which is submitted by DIVYANSHI VERMA, Roll No 2K16/MOC/03 Department of Electronics And Communication Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi **PROF. N. S. RAGHAVA**
Date: **SUPERVISOR**

ACKNOWLEDGEMENT

I would like to thank my supervisor, Prof. N. S. Raghava, Department of Electronics and Communication Engineering, DTU for the guidance, encouragement and advice he has provided throughout my time as his student. I have been extremely lucky to have a supervisor who cared so much about my work and who responded to my questions and queries so promptly. I attribute the level of my Master's degree to his encouragement and effort and without him this thesis, too, would not have been completed or written. One simply could not wish for a better or friendlier supervisor.

I am also grateful to Prof. S. Indu, HOD, Department of Electronics and Communication Engineering, DTU for her immense support. I would also acknowledge DTU for providing the right academic resources and environment for this work to be carried out.

Finally, I take this opportunity to extend my deep appreciation to my family and friends, for all that they meant to me during the crucial times of the completion of my project.

Date: Divyanshi Verma

2K16/MOC/03

M.Tech.(Microwave and Optical Commuunication)

ABSTRACT

The main objective of this project is to design and fabricate a wearable wideband antenna. So the antenna with a U-slot patch and hexagonal EBG structure in a honeycomb pattern is designed on Keysight ADS software. A wideband of 38% is obtained with the help of this design with a gain of 9.08. U-slot has the property to improve the bandwidth of the antenna by introducing a capacitive component in the input impedance which cancels the inductive component of the feed. EBG structures have the property to suppress the surface waves due to the high impedance introduced by the periodic structures. This leads to better gain, bandwidth and radiation efficiency. Additionally, it shields the body from the back radiations thus being beneficial for the wearable applications.

Material selection also plays a major role as the antenna has to be flexible and robust. The flexibility of the antenna is because of the materials chosen i.e. copper tape as the conductor with conductivity 5.96×107 S/m and felt as the substrate with permittivity 1.38 F/m. So felt is chosen as the substrate due its wide availability in various thicknesses and copper tape is selected as the conductor due to its availability and ease of fabrication. For fabrication, the patterns were cut out from the copper tape and pasted on the felt and SMA connector was connected.

Then the various parameters are measured and compared to the simulated results. Both the results are almost in agreement. Therefore, we have achieved the objective of design and fabrication of a wearable antenna with a U-slot patch and hexagonal EBG ground. Given its range of frequency, this antenna finds its applications in the WLAN.

TABLE OF CONTENTS

List of Figures

List of Tables

LIST OF ABBREVIATIONS

Abbreviation	Full Form
IEEE	Institute of Electrical and Electronics Engineers
BAN	Body Area Network
WBAN	Wireless Body Area Network
BW	Bandwidth
EBG	Electromagnetic Bandgap
HIS	High Impedance Surface
AMC	Artificial Magnetic Conductor
ISM	Industrial, Scientific and Medical
WLAN	Wireless Local Area Network
GSM	Global System for Mobile Communications
GPS	Global Positioning System
VSWR	Voltage Standing Wave Ratio
dB	Decibel
mm	Millimeter
%	Percentage
GHz	Giga Hertz
S/m	Siemens per meter
F/m	Farads per meter
SAR	Specific Absorption Rate

FBR	Front to back ratio
ADS	Advanced Design System
SMA	SubMiniature version A

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

These days' people like to do everything on the go, which brings the focus of technology on mobility and portability. This leads to the emergence of portability as the most important trend in communication these days. Therefore wearable technology came into existence as it offers the users the freedom to do their daily activities while providing them with various services. The goal is that the user can carry on with his routine while the wearable gadget or device does its job without providing any hindrance.

Wearable technology is dedicated to wearing or involves incorporation in the clothes or can be attached to a body part, so it has to be flexible or conformal. The modern communication systems cover a wide range of applications like data transfer, voice communication, positioning, health monitoring, entertainment etc. And according to the specific requirements of the masses the wearable technology finds applications in fields like medical, sports, rescue and security services, entertainment and even fashion. Smart watches are the most common example of wearable technology these days. They can monitor your heart beat, count your steps and calories burned, provide notifications etc., while being all fashionable on your wrist.

For the understanding and classification of different wearable aspects, the Institute of Electrical and Electronics Engineers (IEEE), IEEE 802, established a task group in December 2006, entitled IEEE 802.15.6, for standardizing Wireless Body Area Network (WBAN) applications [1]. A general idea about the concept of WBAN [2] is illustrated in Fig. 1.1.

WBANs can be divided depending on the type of communication in the following three categories:

On-body, communication occurring within the same body (wearer), **Off-body**, communication occurring between the body (wearer) and an external unit, and **In-body**, communication between the device mounted on the body and an implanted device in the body [3-5].

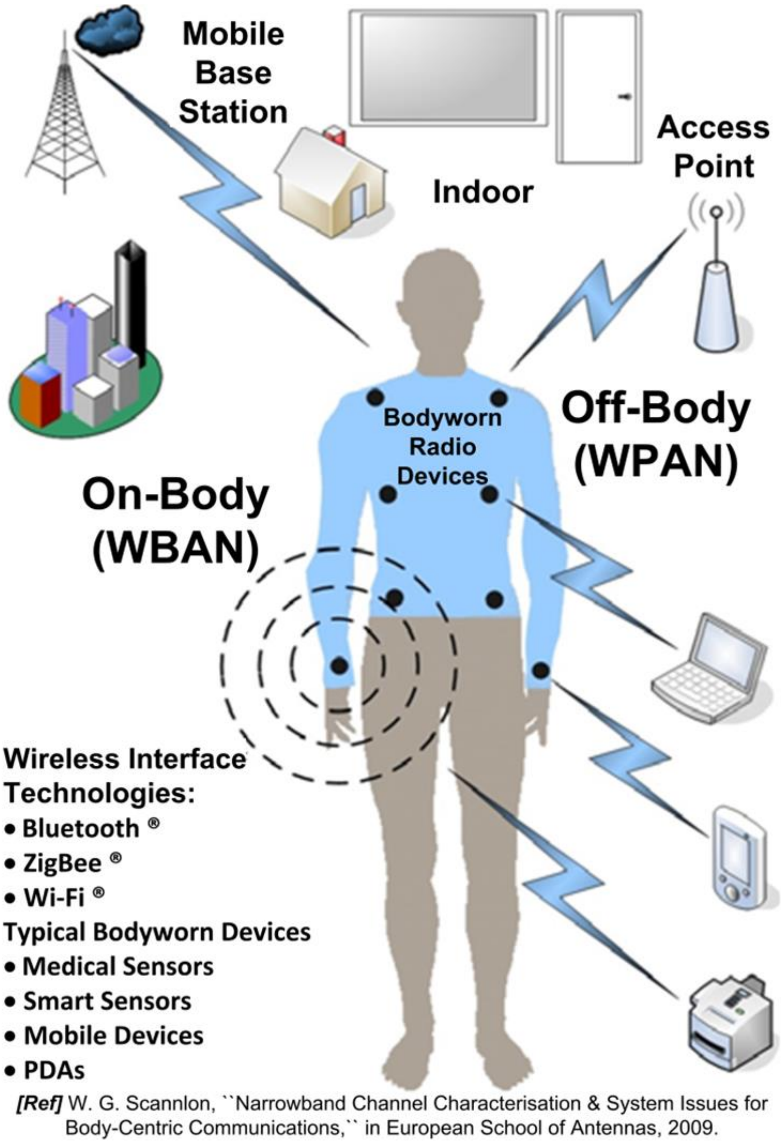


Fig.1.1 Wireless Body Area Network (WBAN) concept [2].

On-body communication occurs when different wearable units are placed on the same body. The different devices are capable of communicating between themselves and can forward all the data which is collected in another central device or master device or hub. From here all the collected data is further sent to an external unit. These days on-body communication is mainly contemplated for health monitoring and sports tracking.

The communication occurring between the external unit and any of the devices mounted on the body is defined as an **Off-body** communication. Therefore the communication between the external unit and the hub device is also an example of Off-body communication. The external units can be smart phones, computers, or even other wearable devices placed on a different wearer nearby, which actually brings in a different sub-group of off-body communication, called **Body-to-Body** communication. Body-to-Body communication is widely spread in different security and rescue service applications, where in some situation the wearers communicate directly between themselves, without using base stations or other intermediate points.

In-body communication is the last category of WBANs. In-body links supply a link between an implanted device and a device mounted on the wearer. The In-body approach shortens the path and creates a link with the device mounted on the wearer, instead of communicating with an external unit. In this way we can solve the problem of strong attenuation which is created by the human body's lossy nature. This communication is largely used for medical purposes [6,7].

1.2 STATEMENT OF THE PROBLEM

In recent years, there has been an upsurge in the wearable electronic applications in the commercial market. But micro-strip patch antenna has narrow bandwidth and low gain characteristics, which no longer makes it a suitable option.

In fabrication of conventional antennas metals and insulators are typically used. But they are stiff and therefore are not flexible and comfortable to be used on the body. The antennas also need to have a low profile, be light weight and tolerant to bending to increase its portability. Therefore in conclusion there is a requirement for flexible materials to design the wearable antennas since the conventional antennas are not fit for wearable applications.

1.3 OBJECTIVE

This thesis is focused on the development and design of a sturdy wearable antenna for communication using the WLAN. The offered wearable antenna should have good performances in different scenarios like in contact with the body or while bending. The antennas should prerequisite to maintain robust and reliable communication links.

The problem of low bandwidth and low gain could be overcome by changing the structure of microstrip antenna by implementing a U-slot on the patch, using a multilayer substrate and including an EBG (Electro Band Gap) structure in the ground, ultimately providing a wideband and higher gain.

Since a wearable device should be conformal, easy to integrate on the body and should not provide any hindrance or discomfort to the user, we used fabric as the substrate. The user can easily wear or attach the wearable device onto their clothes. So, it solves the problems of limited movements or discomfort to the user.

1.4 LITERATURE REVIEW

The primary investigation on wearable antennas was distributed in 1999 where a double band planar antenna was intended for wearable gear [8]. Here a PIFA was reexamined by acquainting a U-slot to obtain a dual band antenna which works at Bluetooth 2.4GHz band and GSM 900. Despite the fact that the regular materials were utilized as a part of this outline which were inflexible however the foreseen thought was to put this reception apparatus on the client's sleeve to make it a wearable antenna. The ground plane acted as a reflector of radiation by forming a shield which stopped the radiation to radiate in the direction of human body.

In [9] they investigated distinctive fabrication procedures of material reception apparatus. Copper tape, copper thread and conductive spray were utilized as conductors to see their impact on wearable antennas.

In [10] an approach is made to gauge the dielectric constant of various textile substrate materials so they can be utilized for the advancement of wearable antennas. The system expressed here depends on the resonance method and concentrated on the utilization of microstrip patch radiator, where textile material is utilized as its substrate. The exact estimation of the dielectric constant of the textile can be obtained from the resonant frequency of the patch radiator.

In [11] a circularly polarized patch is made by truncating the opposite edges of the square patch of the antenna. A comparison is made between the different characteristics using the textiles as substrate materials like jeans, felt and cotton. Which concludes that different substrate permittivity affects the size and performance of the antenna. Jeans as substrate provided superior reflection coefficient and a good AR bandwidth. Whereas the felt substrate achieved a better gain with high dielectric permittivity. Furthermore, the cotton fabric which has lowest dielectric permittivity can be used in antenna miniaturization.

The original U-patch antenna design was realized effectively for wearable technology using copper tape as the conductor and fleece textile as the substrate [12]. In [13] a U-slot patch is created on the copper printed patch and foam is used as the substrate. A detailed analysis shows that U-slot causes an increase in the bandwidth of the antenna by 27%.

Electromagnetic bandgap (EBG) structures also known Artificial Magnetic Conductor (AMC) or High Impedance surface (HIS)[14] are increasingly used in antenna proposals. This is because of their unique electromagnetic properties of stop band for propagation of surfaces waves and in-phase reflection of plane waves. Because of these properties it has been possible to design low-profile antennas [15] and to improve gain, bandwidth and to reduce the backward radiation [16]. The first antenna design based EBG for wearable application was suggested in [17]. Even though it was assembled using inflexible FR4 substrate, it was implemented for wearable uses. Circular slots were etched in the ground plane to form the PBG (photonics band gap) structure.

1.5 THESIS OUTLINE

This chapter started with an preliminary discussion about the wearable technology. Later it centers around the issues which prompt the inspiration and need behind the research in this thesis. A literature survey is written to draw attention towards the developments in this field till now and how this project came into existence.

The 2nd chapter will shed some light on the basics on antenna, definitions, antenna parameters, microstrip antenna and feeding techniques. It provides the foundation of the terms used later in the thesis.

The 3rd chapter starts with the wearable antenna and its applications. Then it focuses on the materials used for the wearable antennas mainly textiles as substrates. Then a brief introduction is given about the fabrication techniques used for the wearable antennas.

The 4th chapter is about the methodology followed for the development of the wearable antenna, from antenna design, simulation to the fabrication. The design of the antenna is explained in detail with material selection, the U-slot design and EBG structure design. Then the fabrication process is explained.

The 5th chapter focuses on the results obtained after simulation on Keysight ADS. The results are compared for design with only EBG, with only U-slot and lastly with both U-slot and EBG. So the design with both U-slot and EBG is fabricated. Then the simulated and measured results are compared. The chapter ends with the conclusions and future scope.

CHAPTER 2

ANTENNA THEORY

2.1 BASICS OF ANTENNA

2.1.1 Antenna Definition

Antenna is an indispensable element of a communication system. It is used to send or receive electromagnetic waves. According to the IEEE definition, antenna is defined as [18]:

“That part of a transmitting or receiving system that is designed to radiate or receive radio waves”.

Therefore, it is a passive element which can create a wireless connection between devices. They have the same properties while transmitting or while in receiving mode hence also called reciprocal devices.

2.1.2 Radiation Pattern

According to [19] the radiation pattern of an antenna is defined as “a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization.”

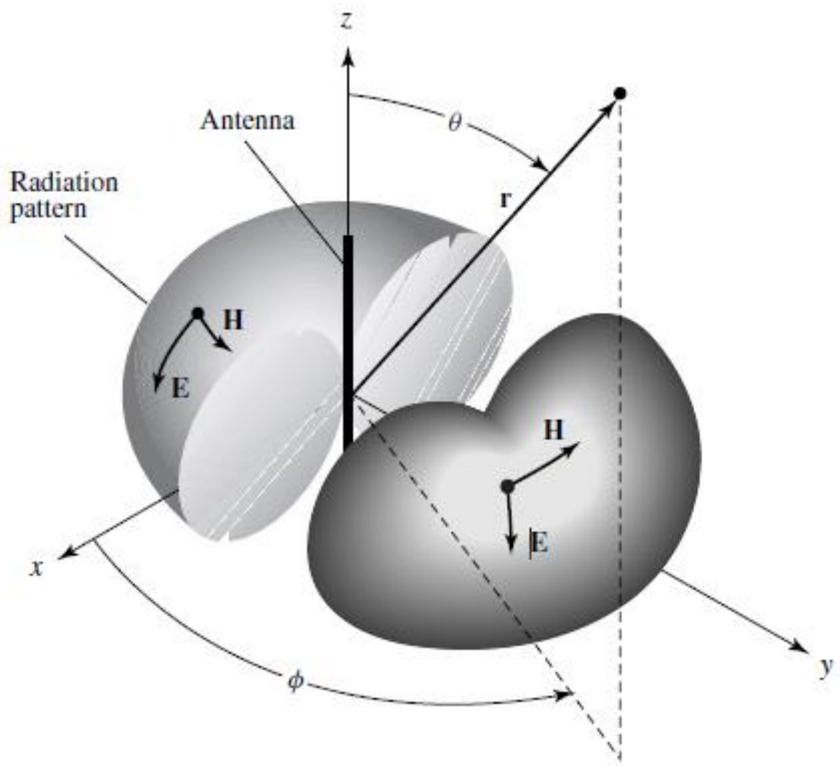


Fig.2.1 Omnidirectional Radiation Pattern [19]

2.1.3 Return Loss

According to the maximum power transfer theorem, input impedance of the antenna and of the source impedance should be matched for maximum transfer of power. If mismatch occurs between these impedances, then some part of the transmitted power is reflected back. "The relative value of this reflected power to the input or incident power is called the return loss of the antenna. Generally, the threshold for return loss is -10 dB which means 90% of incident power should be transmitted" [19, 20].

$$\mathrm{RL(dB)} = -20\log|\Gamma| \tag{2.1}$$

Where, Γ is the reflection coefficient.

2.1.4 Voltage Standing Wave Ratio

The VSWR is the degree of impedance mismatch among the transmission line and the load. VSWR is also defined as “the ratio of maximum voltage to minimum voltage” [21].

$$\text{VSWR V}(\rho) = \frac{V_{max}}{V_{min}} = \frac{1+\Gamma}{1-\Gamma} \quad (2.2)$$

2.1.5 Bandwidth

The Bandwidth of the antenna is defined as “the range of frequencies in which antenna operates. The range of frequency is the difference between the upper cut-off frequency and lower cut-off frequency.” Percentage bandwidth can be written as [21],

$$\text{BW (\%)} = \frac{2 \text{ x}(\text{F}_{\text{upper}} - \text{F}_{\text{lower}})}{(\text{F}_{\text{upper}} + \text{F}_{\text{lower}})} \quad (2.3)$$

2.1.6 Gain and Directivity

The “Directivity is the measure of power an antenna radiates in a particular direction as compared to its radiation in any other direction. It is equal to the power gain if the antenna is 100% efficient. Directivity can also be defined in terms of maximum power density and average value using the following relation” [19],

$$\text{D} = \frac{\text{P}_{\text{max}}}{\text{P}_{\text{average}}} \quad (2.4)$$

According to [19] gain of the antenna (in a given direction) is defined as “the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π.”

$$\text{Gain} = 4\pi \frac{\text{Radiation Intensity}}{\text{Total Input (accepted) Power}} = 4\pi \frac{U(\theta,\phi)}{P_{in}} \qquad (2.5)$$

G and D can be related to each other by the following formula [19]

$$G = kD \qquad (2.6)$$

Where, k is antenna efficiency.

2.2 MICROSTRIP PATCH ANTENNA

The microstrip patch is type of a planar antenna, it comprises of a radiating patch which is attached on one side of the dielectric substrate, and the ground plane is attached on the opposite side. These radiating parts are made of conductors like copper which are commonly photo-etched. The patches are formed in some geometrical shapes like square, rectangular, circular, etc. The fringing fields in the middle of the patch and the ground plane lead to radiation, example as shown in the Fig. 2.2. For these antennas the radiation pattern is perpendicular to the plane of the radiating patch [19].

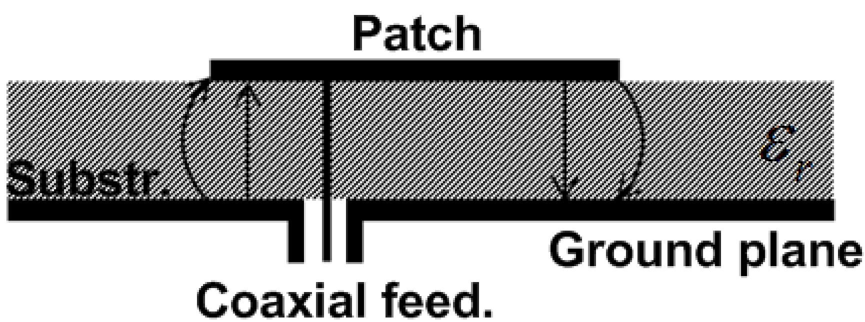


Fig.2.2 Microstrip patch antenna (Cross-section view)

For feeding the patch antennas, different structures can be used, such as coaxial probe, microstrip line, aperture coupling or proximity coupling [19]. The various techniques available for feeding offer a degree of freedom not only while designing, but also in the later stages like while incorporating them on the wearer's body. The microstrip patch finds its application in narrowband wearable antenna, because of its low-profile and flexibility for attaching on the clothes. The existence of ground plane is further beneficial while using in wearable applications, because they prevent the radiations to enter the user's body.

Table.2.1 A summary of the advantages & disadvantages of microstrp antennas

Advantages ☺	**Disadvantages ☹**
Light weight and low volume	Narrow bandwidth
Conformability	Low efficiency
Low cost of fabrication	Low gain
Supports linear and circular polarization	Extraneous radiation from feeds and junctions
High level of integrability	Low power handling capacity
Capable of multiband operations	Surface wave excitation
Mechanically robust	

2.2.1 Feeding Mechanism

Coupling of power in or out of an antenna can be done by a variety of techniques that are broadly divided into contacting and non-contacting [22]. Contacting feed means that there is a direct connection of transmission lines, like in coaxial feed or in microstrip lines. The position of the connection within the boundaries of the patch decides the input impedance [22]. Electromagnetic field coupling is used in non-contacting feeds to transfer the power between the radiating patch and the feed lines. Even though this feeding technique provides more degree of freedom as compared to contacting feed, it is harder to design. The most ordinarily used feeding are microstrip lines, coaxial probe, aperture coupling and proximity coupling.

Microstrip line feed is a type of feeding in which a conducting strip is directly attached to the edge of the microstrip patch like in fig.2.3. The width of the strip is less in comparison to the patch. The advantage of this kind of feeding is that the strip can be etched on the same substrate thus providing a planar assembly. The inset cut of patch is made to create impedance matching between the feed line and the patch. Consequently, it is easier to fabricate and simpler to match by adjusting the point of the inset.

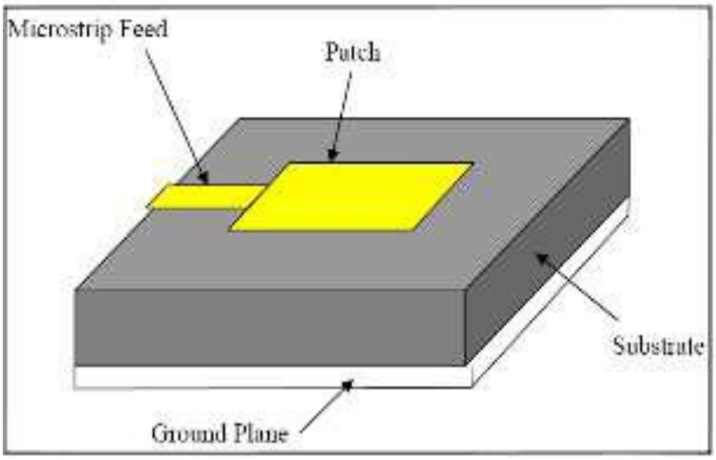


Fig.2.3 Microstrip Feed

Coaxial cable consists of two concentric cylindrical wires which are separated by a dielectric material. In coaxial feed method, outer conductor of the coaxial cable is soldered to ground plane while inner conductor is soldered to radiating element. The prime benefit of this feeding system is that the location of the feed can be adjusted to match the impedances to any desired location inside the patch. This technique has lower radiation and is easy to fabricate.

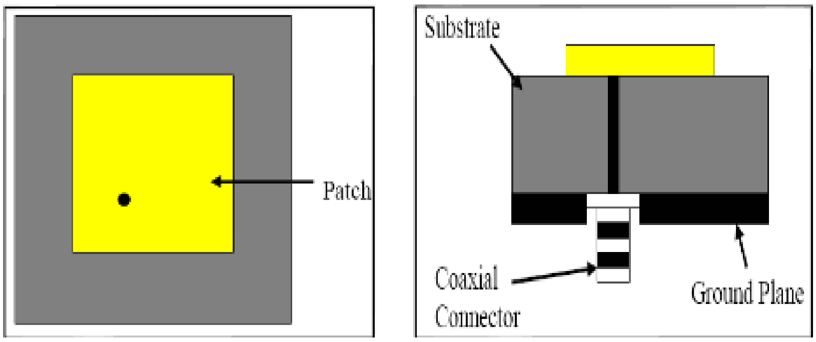


Fig.2.4 Coaxial Feed

CHAPTER 3

WEARABLE ANTENNA BACKGROUND AND OVERVIEW

3.1 WEARABLE ANTENNAS APPLICATIONS

3.1.1 Security and Rescue Service Applications

The fundamental focus is on robust wearable antennas for these applications as they are anticipated to operate in different harsh environments. Special government regulatory offices standardize the frequency bands proposed for such applications. The most important requirements for this field are resilience of antenna to environment and size miniaturization.

Antennas designed for such applications have to be small, low profile, non-protrusive and conformable so that can be easily around the wearer's body. Another important feature are weather conditions and the environment where these wearable antennas are used. Since these applications require working outdoors, the antenna requirements would be robustness against water, rain, moisture, mud, etc. These are applicable to military, fire fighters or rescue services. Different parameters like actual position, psychological parameters or environment conditions can be supervised with these antennas attached in garments. For example, the antenna proposed in [23] is an asymmetric dipole antenna exclusively designed for armor vests as shown in fig. 3.1.

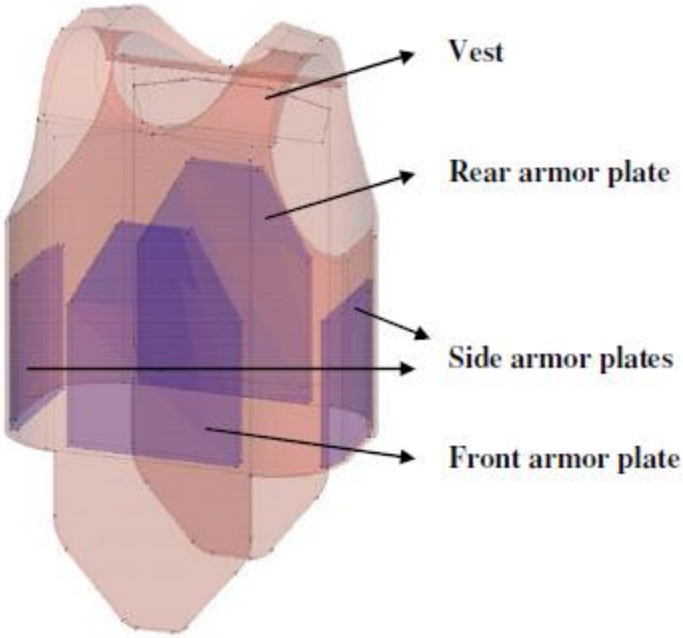


Fig.3.1 Model of armor vest structure for EM simulation [23]

3.1.2 Medical Applications

Medical applications cover a large share of the WBANs. They are primarily utilized for health monitoring of the user or patient. They can monitor different parameters and detect changes continuously 24 hours a day, like heart rate, blood pressure, or body temperature [24]. And due to the more extensive use of smart phones, the data collected from these medical monitoring devices is stored, monitored and even directed to the hospital or doctor in charge [25, 26].

Medical applications will continue to be the leading consumers of the wearable technology. And the continuous progress in the field permits monitoring of numerous health activities and parameters. Also smart phones and other wireless devices like laptops and tablets have the capability to act as trustworthy hubs and transceivers, hence these applications even more promising. Wearable antennas will carry on to be the vital link between the external units and on-body devices.

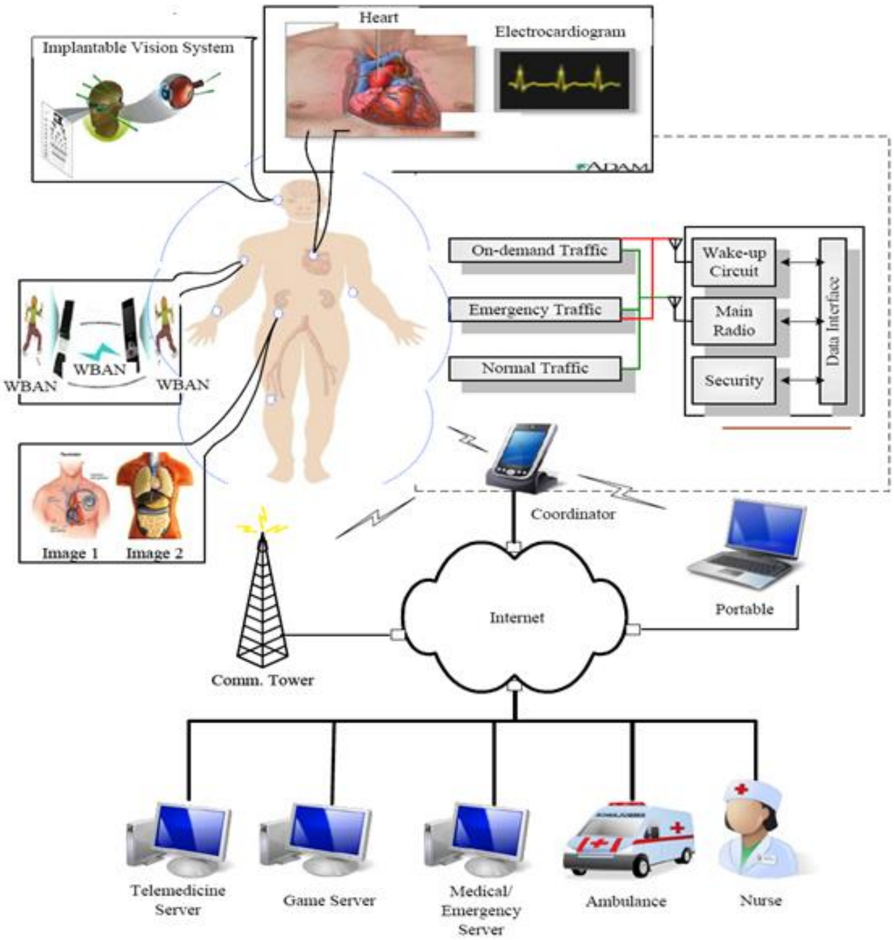


Fig.3.2 WBAN used for Health Monitoring [27]

3.1.3 Sports, Entertainment and Fashion Applications

These days' consumers like to keep track of their performances in all types of sports or physical activities that they do. Parameters like speed, elevation, distance, calories burned, heart rate etc. can be easily tracked and recorded using different wearable applications. Almost all the tracking can be accomplished with the prevailing smart phones; then again some distinct wearable devices are also present. A number of wrist watches called the 'smart watches' are available with built-in GPS antennas that can determine distance, time, position of user and his heart rate [28, 29]. These smart watches are very fashionably designed to attract the masses. They also provide notifications via the smart phones and also used for entertainment purposes like music. Additionally, wearable devices are used more extensively by the professional sportsmen. Since they can improve their performances by continuously monitoring their progress by tracking and analyzing the collected data.

Fig.3.3 Smart Watches for sports and entertainment applications [28, 29]

3.2 WEARABLE MATERIALS

Materials play the most significant role in the design and fabrication of wearable antennas. The incorporation of antennas into clothing of the wearers secondarily inflicts the prospective choice of substrate and conductive materials to be flexible or conformal. A lot of such constituents are established in the literature: textiles, printed conductors, specially treated yarns, polymers, etc. [30-32]. To construct the ultimate antenna designs the carefully chosen materials need to undergo the fabrication processes which are usually unlike the conventional processes.

The performance of the antenna is also dependent on the operating environment. Apart from the influence of the body on antennas, they maybe also affected by the diverse and severe environment, resulting from the weather conditions like humidity, rain, snow, ice, mud etc. So material selection is of utmost importance [33].

3.2.1 Textiles

Textile materials are amongst the most commonly used materials for constructing the wearable antennas. They are light weight and can be integrated in the clothing of the wearer very easily. The proposed textiles need to fulfill certain mechanical, electromagnetic and environmental conditions for the wearable applications.

Considering the EM properties, the conducting materials used for the ground plane and the radiating patch must have good conducting characteristics and low losses. Whereas the dielectric material should have low loss dielectric permittivity and constant thickness [34].

Precautions have to be taken while designing and selecting the material because on one hand, wearable antennas must be flexible or conformable and should remain steady when mounted on the wearer while provide reliable radiation. But on the other hand, the properties of the antenna may be depreciated due to the regular bending and crumpling of the textile [35].

The textile materials commonly used for the fabrication of wearable antennas are divided in two major groups, conductive and dielectric materials. The conductive materials presented in [37] are as follows:

- Conducting Ribbon
- Insulated wire
- Conducting Paint
- Conducting Nylon
- Conducting Thread
- Screen Print
- Coated copper fabric
- Copper tape
- Copper foil

There is a greater variety to choose from when it comes to the selection of dielectric materials. This is because most of the textiles have low relative permittivity and reasonably low loss tangent angle, consequently making them substrates which are suitable for wearable antennas. Since no extra fabrication treatments are necessary, ideally most of the textiles can be used as substrate materials.

Table.3.1 Dielectric materials used for wearable antennas [34-36]

Material	Single layer thickness [mm]	ϵ_r	tan δ
Felt	1.1	1.38	0.023
Woolen felt	3.5	1.45	0.02
Polyamide fabric	6	1.14	Negligible
Fleece	2.56	1.25	Negligible
Closed-cell foam	3.94	1.52	0.012
Silk	0.58	1.75	0.012
Tween	0.68	1.69	0.008
Panama	0.437	2.12	0.018
Moleskin	1.17	1.45	0.05
PTFE	11.66	2.05	0.0017
Cordura	NA	1.90	0.0098
Cotton	NA	1.60	0.04
100% polyester	NA	1.90	0.0045
Quartzel fabric	NA	1.95	0.0004
Cordura/lycra	NA	1.50	0.0093
Jeans textile	1	1.7	0.025
Acrylic textile	0.5	2.6	NA

3.3 FABRICATION METHODS

Manufacturing or fabrication techniques for textile antennas can be classified into the following types:

3.3.1 Thin and Uniform Metallization Conductive Sections

In this process thin and uniform metallized layers of conductors like copper or silver tape, foil which are attached to the substrate textile [38]. It is the fastest and most reasonable method but it is not ideal for a permanent or long term use. The copper tape or foil is easy to stick on the substrate, but it detaches or peels off around the edges after some time due to bending.

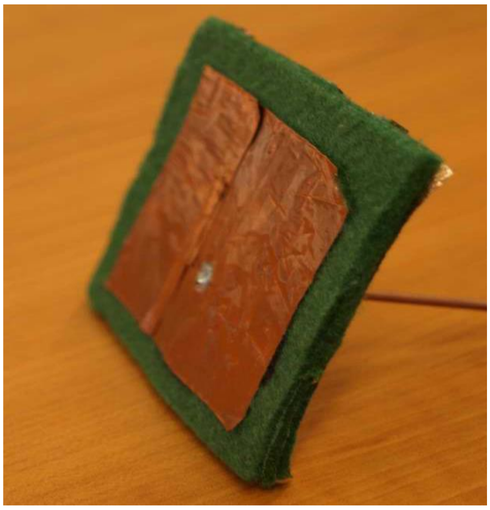


Fig.3.4 Peeled off copper tape due to environmental conditions [39]

3.3.2 Woven or Knitted Conductive Sheets

In the method conductive textile yarns are woven or knitted in the form of conductive patterns or sheets which are then attached or stitched on top of the non-conductive textile substrate of the antenna [38].

3.3.3 Embroidery

In this method the conductive textile yarns used to do to embroidery of the conductive shapes directly on the textile substrate [38]. With the technological advancement it is now possible to directly to the embroidery of a digital image using a computer aided embroidery machine. These conducting threads should be flexible and strong to withstand high tension.

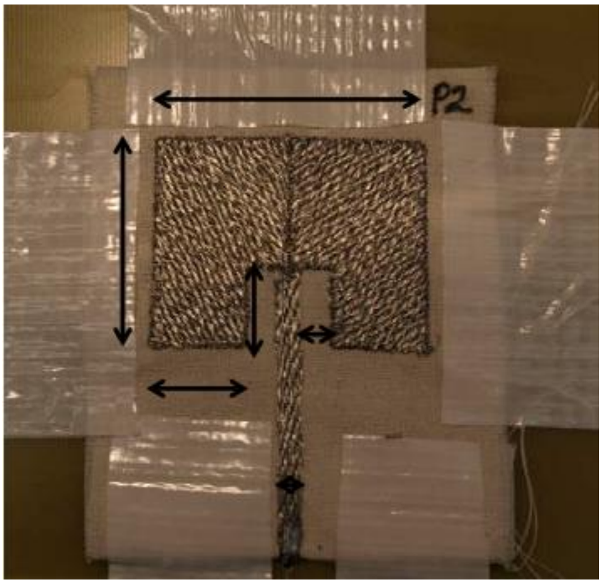


Fig.3.5 Embroidered patch antenna [40]

3.3.4 Inkjet printing and screen printing

It is utilized to generate conducting shapes of antennas. But textiles are not ideal substrates for printing so generally substrates like paper or Kapton are used.

CHAPTER 4

ANTENNA DESCRIPTION

4.1 METHODOLOGY

The design and materials of the antenna have been finalized after a lot of trials and researches. First of all, research was carried out via internet, books, and research papers on wearable antennas. This was done to further develop the understanding about fundamentals, theory and properties of the antenna. Then the aim was to design a wearable antenna which had a wider bandwidth. This is because the drawback of microstrip antenna is that it has a narrow bandwidth. The advantages of a wide bandwidth are as follows

- Large channel capacity
- Coexistence with current narrowband radio service
- Resistance to jamming
- Low transmit power
- Ability to work with low SNRs
- High performance in multipath channels

To achieve a wide bandwidth several designing techniques were taken into consideration like

- Increasing substrate height or substrate stacking
- Decreasing dielectric constant
- Using partial ground
- Including slots
- Using Electronic Bandgap structures

All these methods have their pros and cons. By increasing the height of the patch nullifies the advantages of a low profile and increasing the substrate height depends on the availability and suitability. So the most appropriate technique to increase the bandwidth while maintaining the low profile, compact and simple design is to modify the basic element geometry like creating slots. But this also has a disadvantage that the analysis becomes quiet complex. Therefore even though there have been many designs in papers, the analytical design methodologies are not presented.

The designing and simulation is done using Keysight Advanced Design System 2016.01 [41]. Several options out of these were considered to obtain a wide band wearable antenna. Trials were conducted to achieve the best result using different substrates materials, different substrate thicknesses, different EBG on the ground and different dimensions of the u-slot.

4.2 ANTENNA DESIGN

A simple microstrip patch antenna with a microstrip feed line is chosen because of its easy designing, fabrication and analysis. U-slot is implemented on the rectangular patch of 50mmx50mm and hexagonal honeycomb structure is cut out from the ground conductor to form the EBG ground structure of 90mmx110mm. Different options were considered for thickness of substrate, u-slot and EBG to finally reach to this design as shown on fig.4.1.

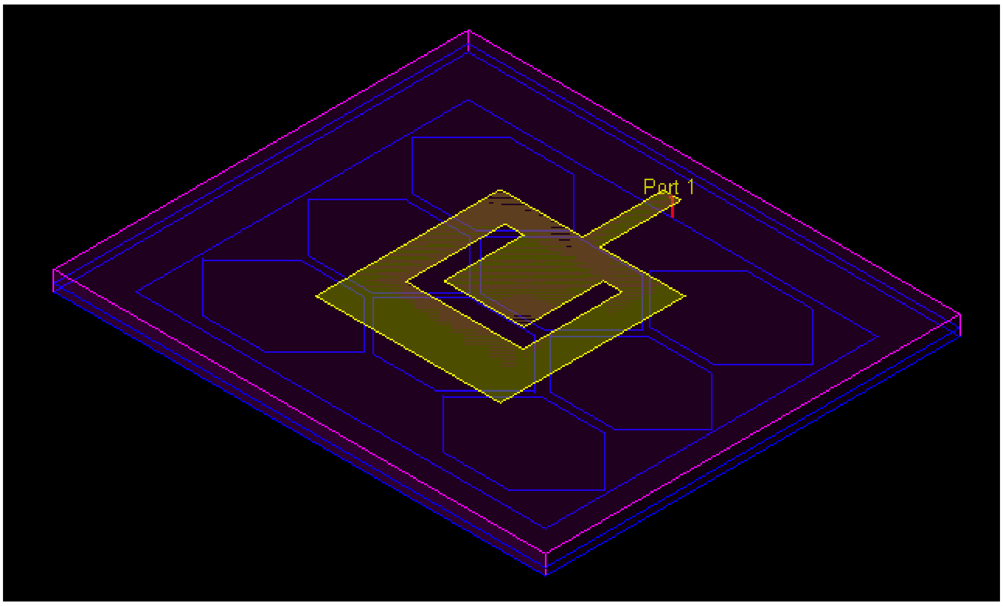


Fig.4.1 Designed Antenna on ADS software

4.2.1 Material Selection

Firstly the materials to be selected had to be flexible so felt and copper tape (of 0.25mm thickness) were the best candidates for substrate and conductor respectively. The felt is further chosen as the substrate because it has lowest permittivity than other available textiles like jeans or cotton, and that is required for wideband property. For wideband applications two layers of felt were used of 2 mm and 3.2 mm. The value of permittivity of felt substrate is derived from the research papers as 1.38 F/m [34-36]. For the conducting part copper tape is used because of its easy availability and ease of being stuck on the substrate. Conductivity of copper is 5.96×10^{7} S/m.

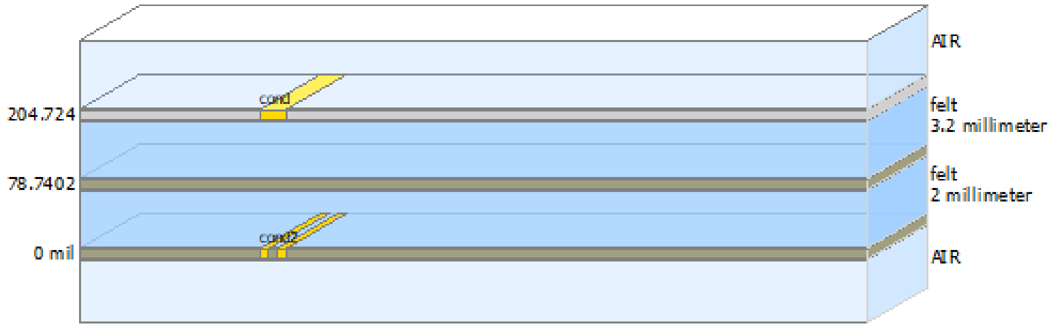


Fig.4.2 Material Design of Antenna in ADS software

4.2.2 U-Slot Design

Experiments have shown that variations in the dimensions of the U-slot like its length or width or even the height or size of the patch alter the antenna's behavior very drastically. There are no analytical methods available to be able to explain the complex relationship between U-slot dimension and characteristics.

To obtain a dual band operation antenna has to be loaded reactively. And when two or more resonance frequencies come sufficiently close to each other we acquire a broad band. The U-slot acts in such a way that it introduces a capacitive component in the input impedance of the antenna; as a result the inductive component of the probe feed and/or the currents around U-slot is reactively cancelled. The U-slot patch antennas demonstrate broad-band characteristic because these antennas have a low Q-factor. The thickness of the substrate is inversely proportional to the Q-factor [42-45]. The appropriate modifications in the width and the length of the U-slot also contribute to its wideband behavior.

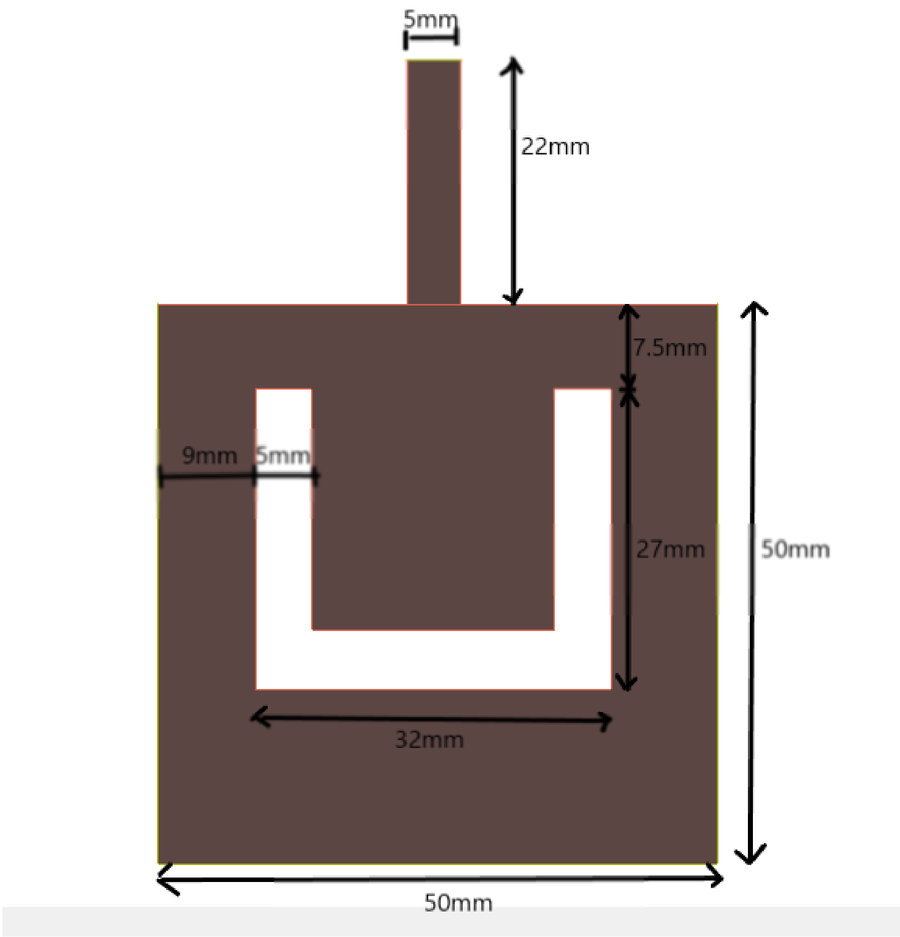


Fig.4.3 Patch of the Antenna with the U-slot

The U-slot in the patch can be regarded as an arrangement of three narrow slots combined together in the form of U-shape. The equivalent circuit of U-slot can be considered as shown in fig.4.4 by using duality relationship of dipole and slot [48].

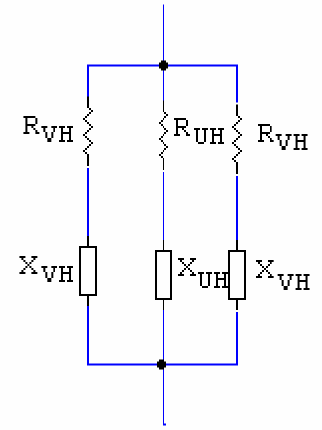


Fig.4.4 Equivalent circuit of the U-slot

Where, R_{UH}, X_{UH} and R_{VH}, X_{VH} are reactive component of the base-arm and side-arm of the U-slot.

Since the equivalent circuit of a patch is a parallel combination of resistance, inductance and capacitance as shown in fig. 4.5, therefore on combining that circuit with the equivalent circuit of U-slot we get fig.4.6.

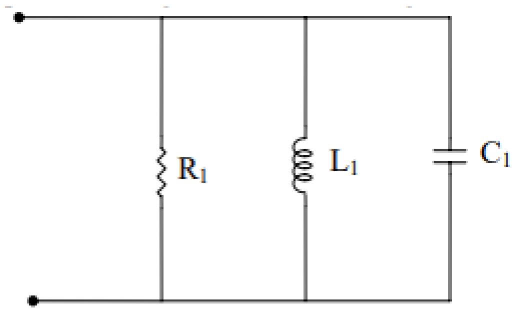


Fig.4.5 Equivalent circuit of patch

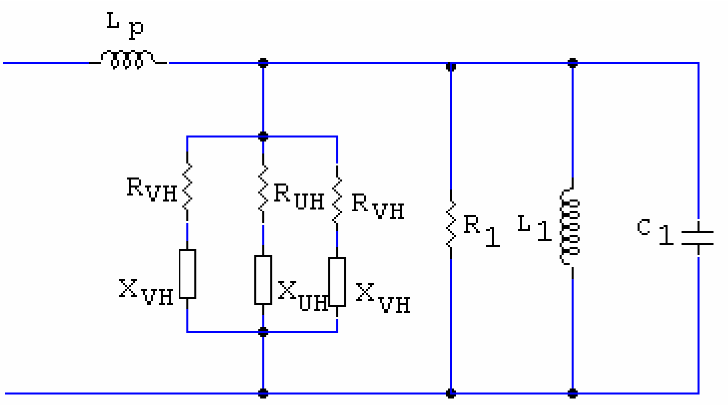


Fig.4.6 Equivalent circuit of the U-slot with patch

4.2.3 EBG Structure

Electromagnetic bandgap (EBG) structures are also referred as High Impedance surfaces (HIS) or Artificial Magnetic Conductor (AMC). Generally, EBG structures are defined as "artificial periodic structures that avert or assist the propagation of electromagnetic waves in a specified band of frequencies for all incident angles and all polarization states."[49] These structures are being used frequently in conventional antenna designs these days because of their two distinctive electromagnetic properties of

- in-phase reflection of plane waves
- suppression of surface waves

These properties have been widely used in designing low profile antennas and improving the bandwidth, gain and backward radiation in patch antenna designs [46, 47]. The in-phase reflection of the plane waves assists in a low profile antenna design. The high surface impedance suppresses the surface waves thus creating a band gap for the surface wave, therefore the name Electromagnetic band gap (EBG). EBG structures have been incorporated with antennas to increase the antenna efficiency and gain and decrease backward radiations.

Surface wave suppression leads to decline in the back and side lobes and increase in the front to back ratio (FBR) due to which the radiation efficiency and gain are improved. In addition, due to the decrease in backward radiations, Electromagnetic Band Gap structures provide shielding for the human body from EM radiations, consequently decreasing the Specific Absorption Rate (SAR). Thus, adding to the advantage of a wearable antenna because when the body is exposed to the incident radiations for a long time there is an increase in the body temperature which causes damage to the tissues.

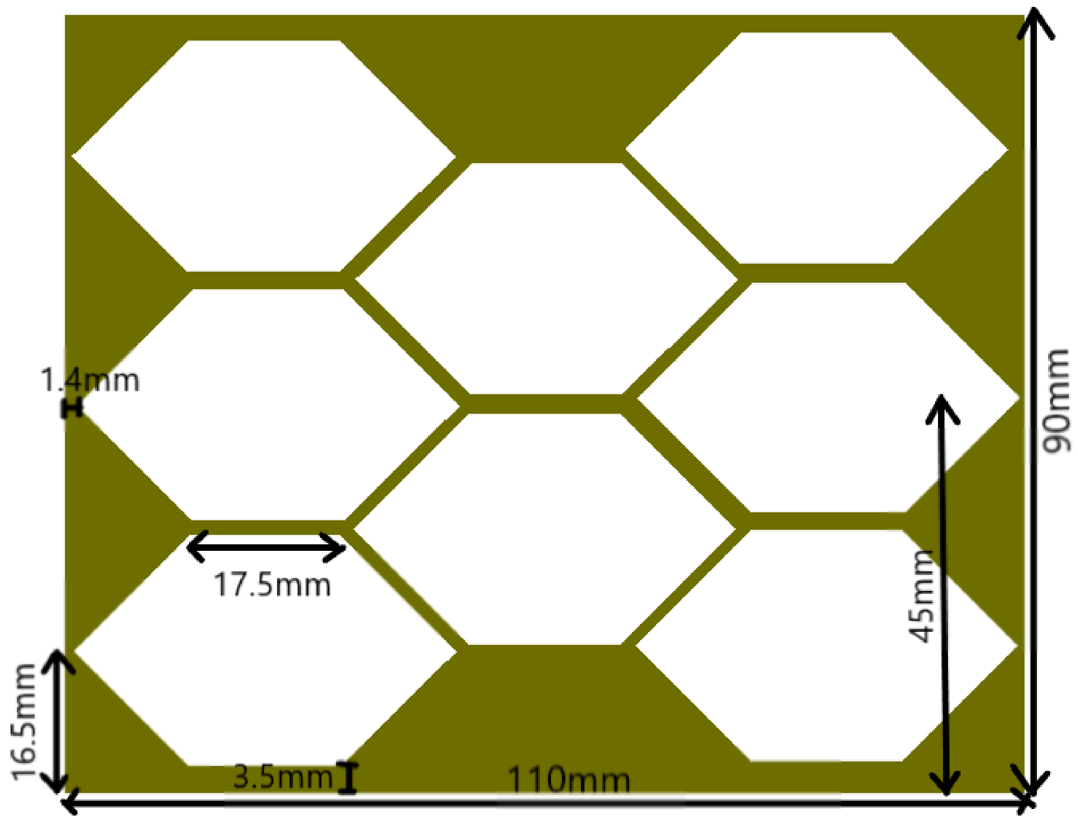


Fig.4.7 Ground of the antenna with hexagonal EBG structure

4.3 FABRICATION

For the fabrication, unconventional methods were to be used because the materials used cannot undergo the conventional fabrication.

1. Two layers of felt of thickness 2 mm and 3.2 mm were cut into substrates of given dimensions 9cm x 11cm using scissors. Then these two layers were fixed together using glue to form a stacked substrate.

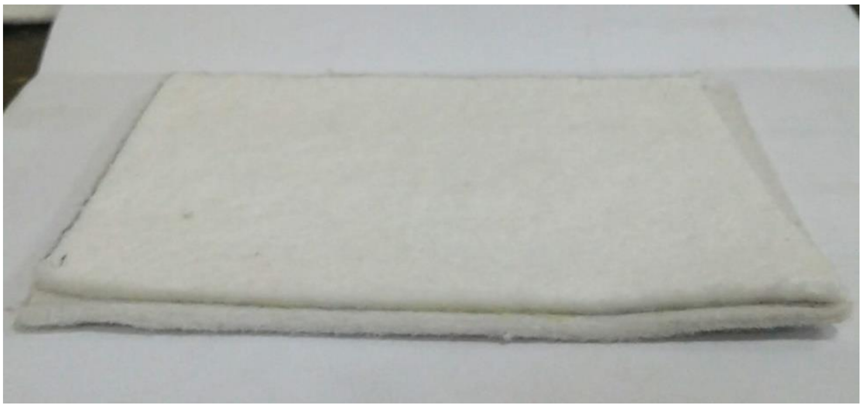


Fig.4.8 Two layers of felt are stuck together using glue

2. Then the pattern of U-slot and hexagons were cut out from copper tape and were pasted on the felt. The U-slot was pasted as a patch on one side and the hexagonal EBG was pasted on the other side forming the ground. Since the pattern was very fragile the other option to be considered is to first paste the tape on the felt and then cut out the pattern.

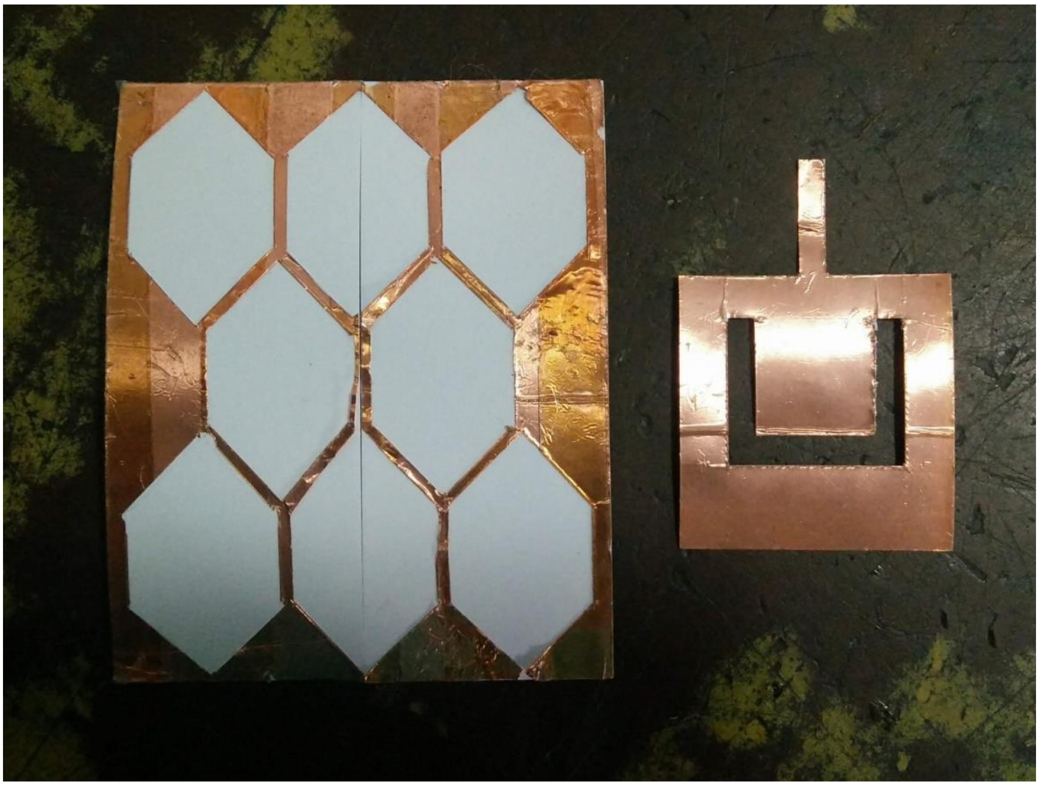


Fig.4.9 Pattern cut-outs from the copper tape

3. Then the SMA connector was soldered on the conducting part. And the final antenna was ready.

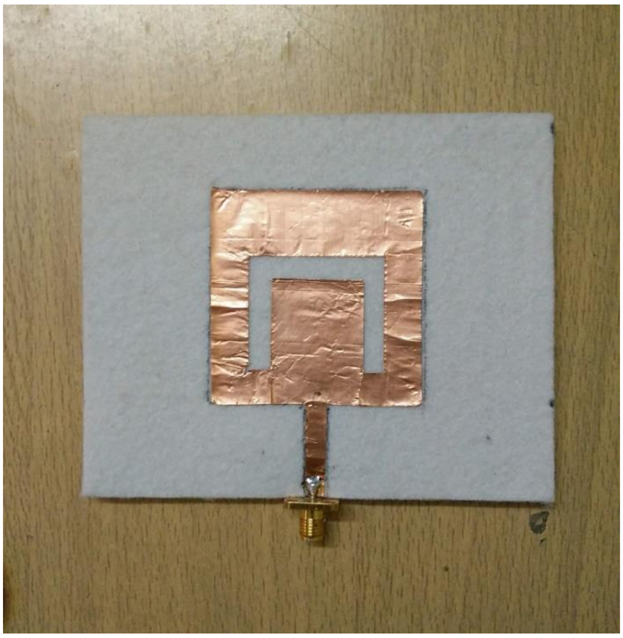


Fig.4.10 Front view of the final fabricated antenna

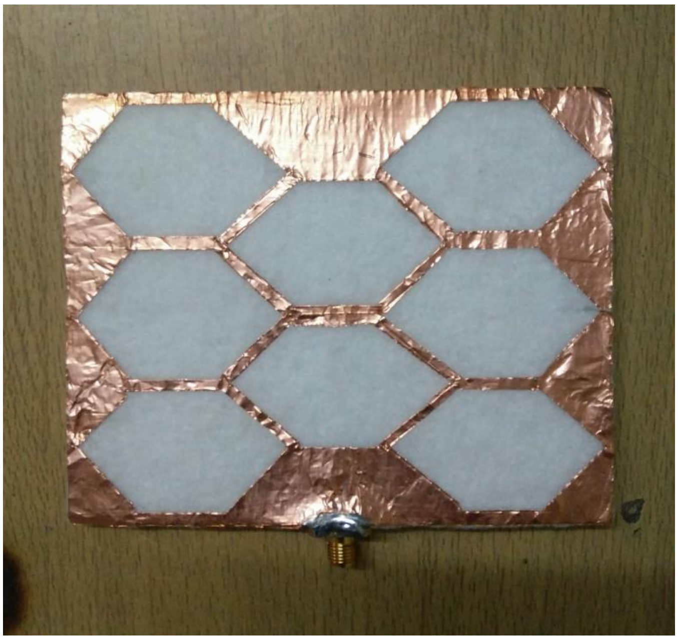


Fig.4.11 Back view of the final fabricated antenna

CHAPTER 5

RESULTS AND CONCLUSION

5.1 SIMULATION RESULTS

The simulation procedure of the proposed antenna was carried out on Keysight ADS [41]. Several modifications were made and trial simulations were run to reach the final antenna design. The simulation was conducted with and without the presence of U-Slot and EBG to provide a basic difference between the results and to see the effects of both U-Slot and EBG separately. The simulation results will be divided into three designs:

1. Patch without U-Slot and Ground with EBG
2. Patch with U-Slot and Ground without EBG
3. Patch with U-Slot and Ground with EBG

5.1.1 Patch without U-Slot and Ground with EBG

The antenna design with only EBG structure on the ground was simulated to observe the results due to the presence of EBG ground without U-Slot on the patch. This was done to see effects of only the EBG structure on the antenna exclusively. The results observed are as follows. It shows dual band antenna having two operating frequencies at 2.4 GHz and 5.5 GHz. But since we want a broadband antenna we still prefer modifications.

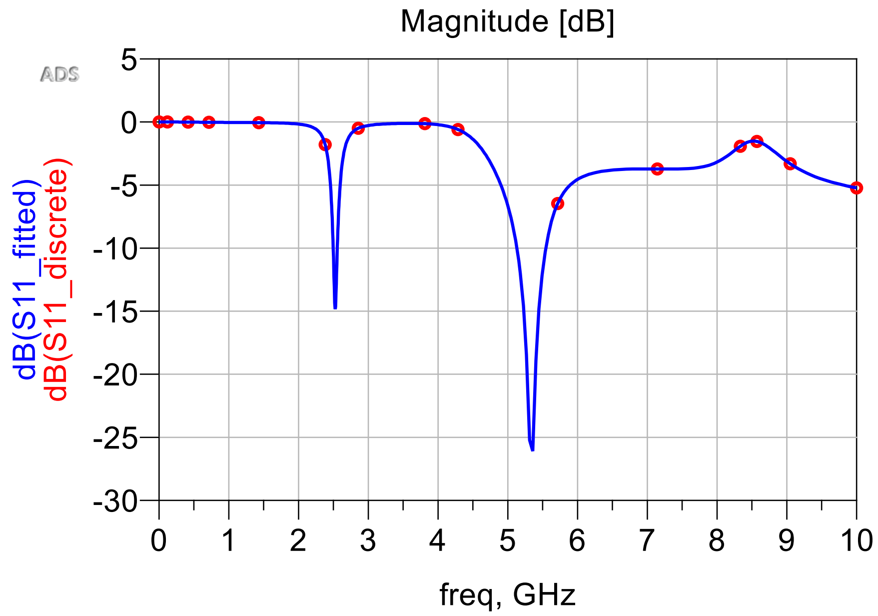


Fig.5.1 Simulated result of S11 parameter

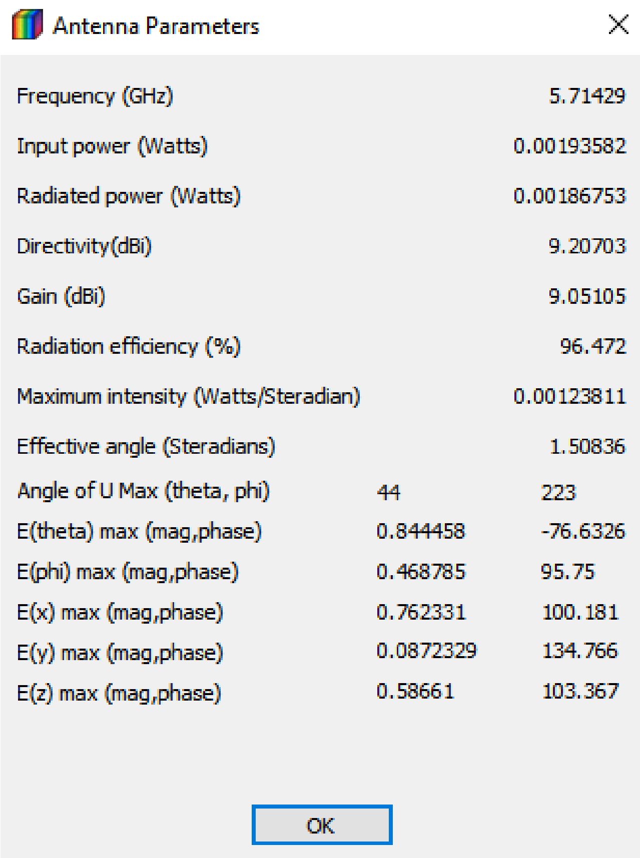


Fig.5.2 Simulated results of various antenna parameters

5.1.2 Patch with U-Slot and Ground without EBG

The antenna design with only U-Slot structure on the patch was simulated to observe the results due to the presence of U-slot in the absence of the EBG structure. This was done to see effects of only the U-slot on the antenna exclusively. The results observed are as follows. Here we can see that the U-slot gives rise to a wideband result. But to improve the bandwidth some modifications are preferred.

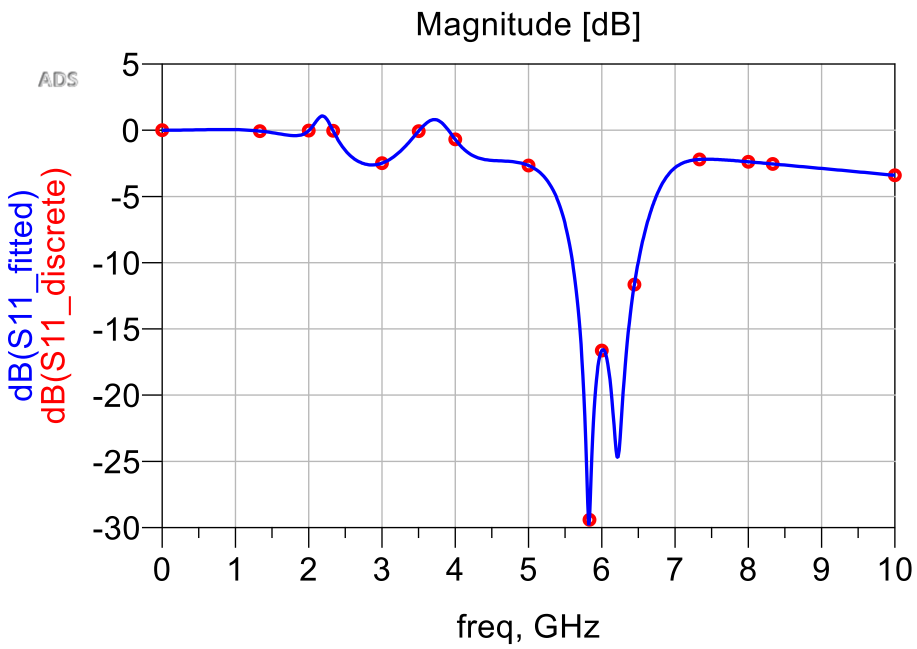
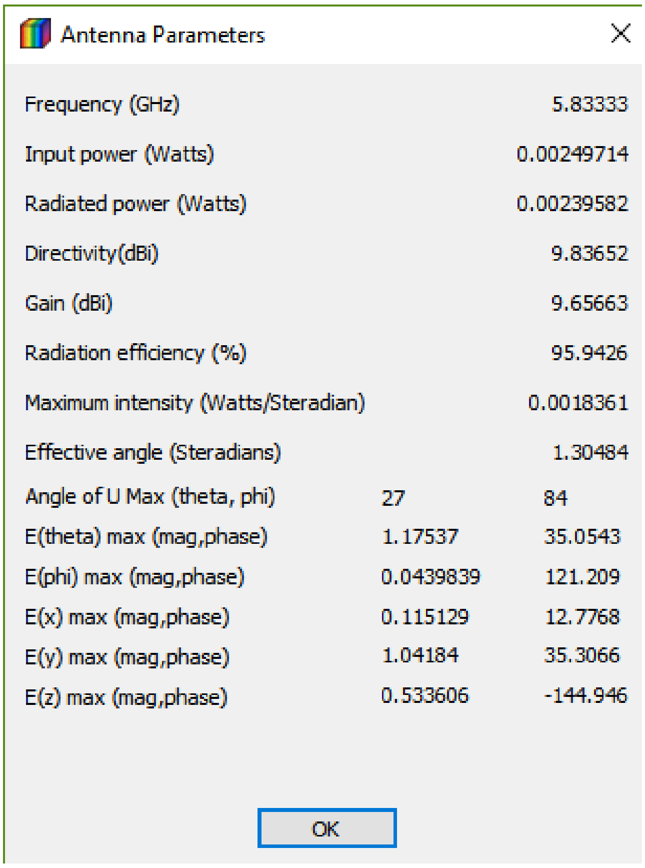


Fig.5.3 Simulated result of S11 parameter


Antenna Parameters

Frequency (GHz)		5.83333
Input power (Watts)		0.00249714
Radiated power (Watts)		0.00239582
Directivity(dBi)		9.83652
Gain (dBi)		9.65663
Radiation efficiency (%)		95.9426
Maximum intensity (Watts/Steradian)		0.0018361
Effective angle (Steradians)		1.30484
Angle of U Max (theta, phi)	27	84
E(theta) max (mag,phase)	1.17537	35.0543
E(phi) max (mag,phase)	0.0439839	121.209
E(x) max (mag,phase)	0.115129	12.7768
E(y) max (mag,phase)	1.04184	35.3066
E(z) max (mag,phase)	0.533606	-144.946

OK

Fig.5.4 Simulated results of various antenna parameters

5.1.3 Patch with U-Slot and Ground with EBG

The antenna design with the presence of U-Slot structure on the patch and the EBG structure on the ground was simulated to observe the results due to the presence of both U-slot and EBG structure together. The results observed are as follows. This design is the final design as it provides the best results after simulation in terms of a wide bandwidth. As we can see the bandwidth has improved a lot and reaches to almost 38.5% bandwidth. Also as we can see in table 5.1, since the other parameters like gain, directivity and efficiency do not really differ that much, we choose this design to be the best in terms of overall results, given our requirement of a wide band. As a consequence, this design is fabricated.

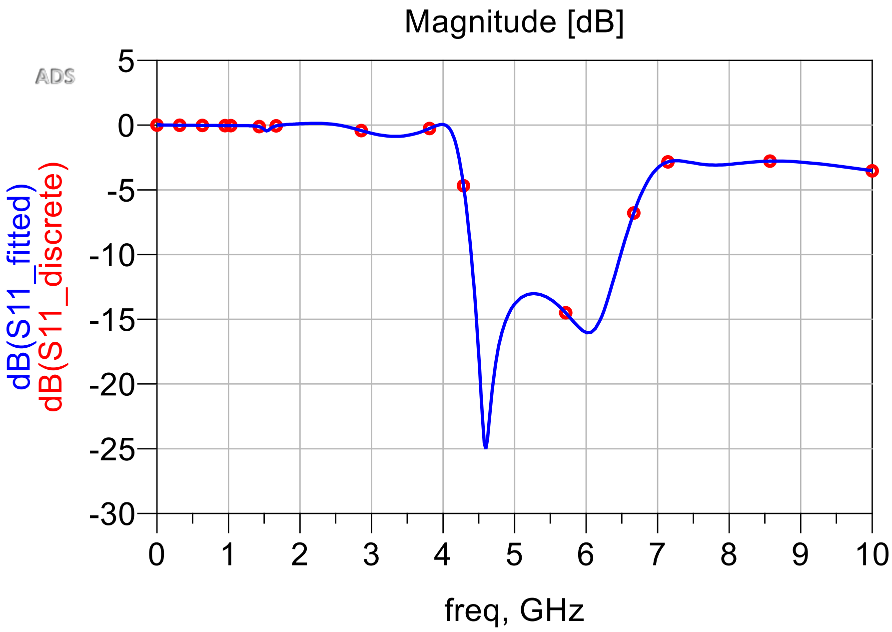
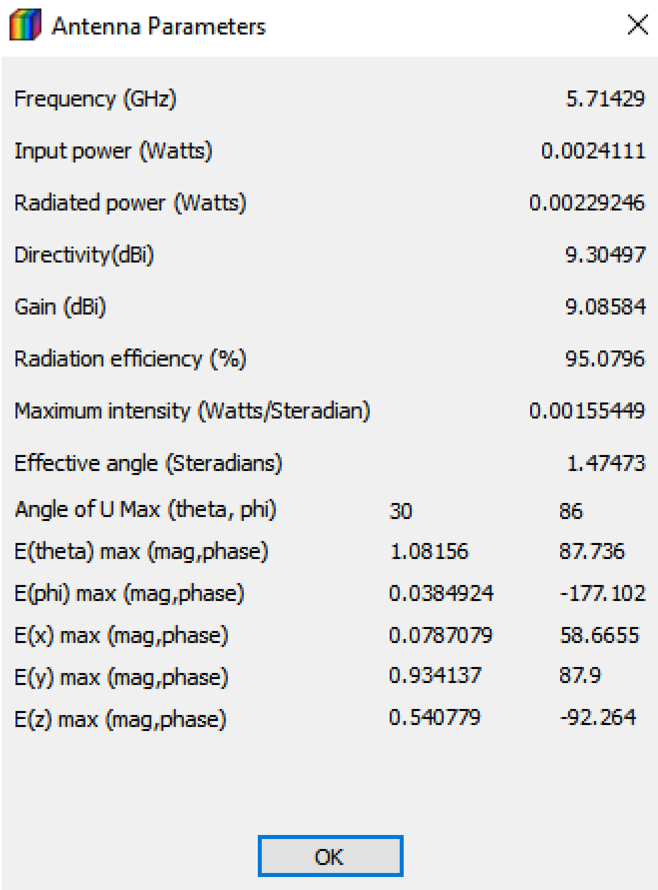


Fig.5.5 Simulated result of S11 parameter



Antenna Parameters

Frequency (GHz)		5.71429
Input power (Watts)		0.0024111
Radiated power (Watts)		0.00229246
Directivity(dBi)		9.30497
Gain (dBi)		9.08584
Radiation efficiency (%)		95.0796
Maximum intensity (Watts/Steradian)		0.00155449
Effective angle (Steradians)		1.47473
Angle of U Max (theta, phi)	30	86
E(theta) max (mag,phase)	1.08156	87.736
E(phi) max (mag,phase)	0.0384924	-177.102
E(x) max (mag,phase)	0.0787079	58.6655
E(y) max (mag,phase)	0.934137	87.9
E(z) max (mag,phase)	0.540779	-92.264

OK

Fig.5.6 Simulated results of various antenna parameters

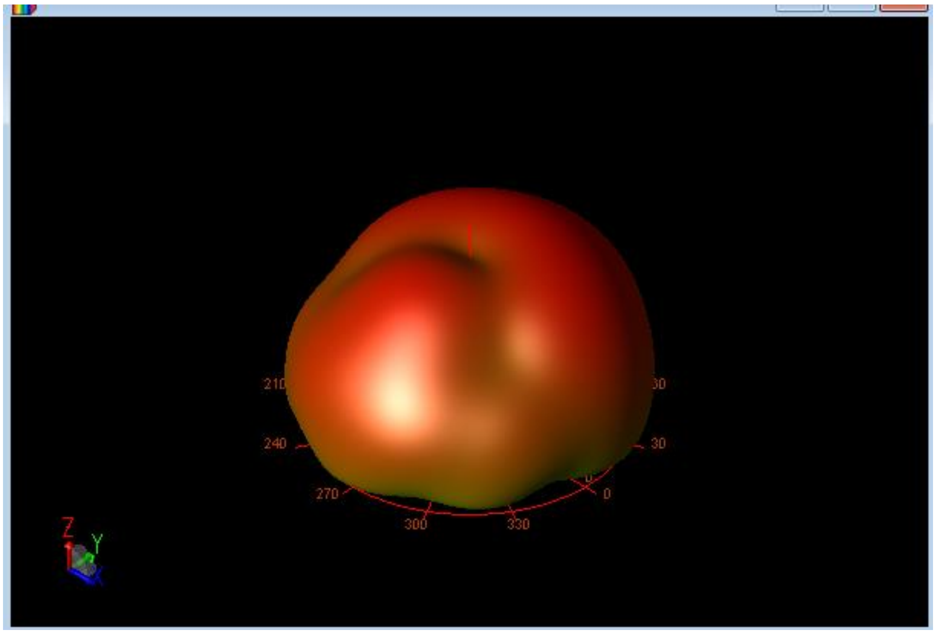


Fig.5.7 Radiation Pattern of the final antenna

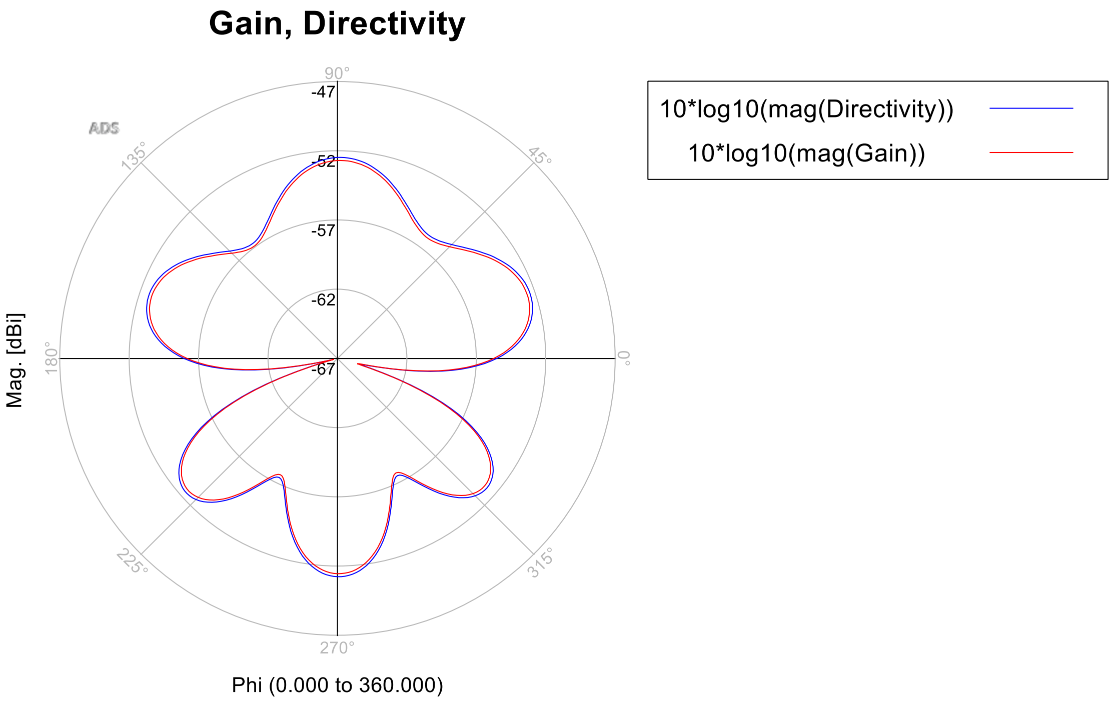


Fig.5.8 Polar plot of Gain and Directivity (Theta=90º)

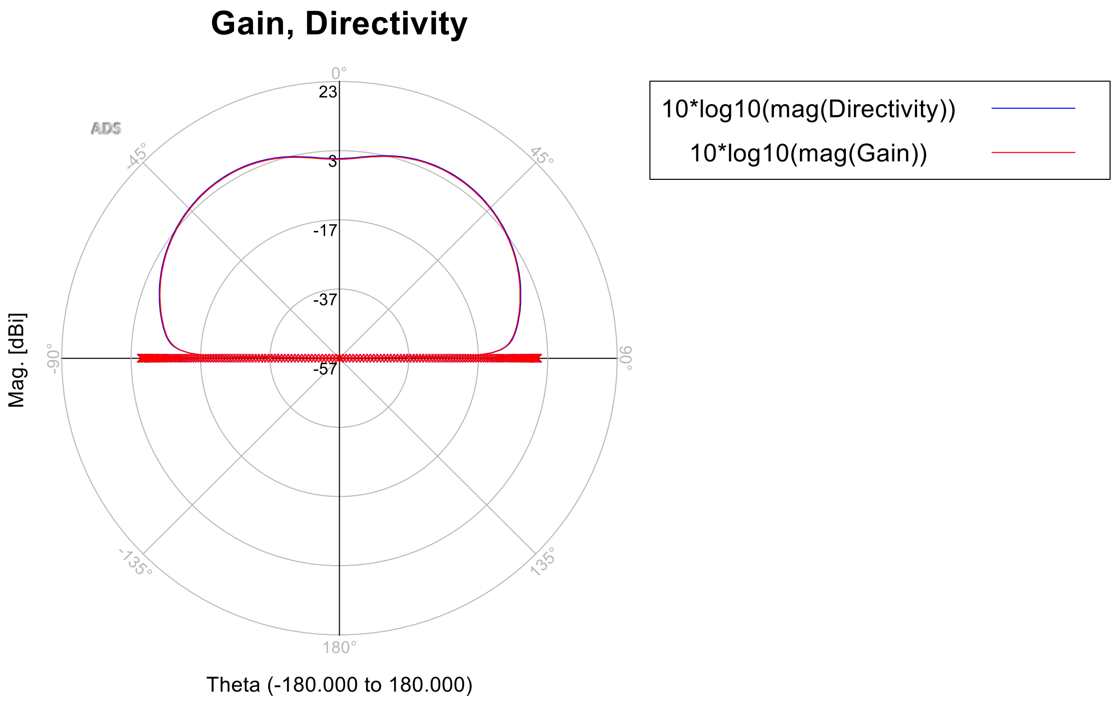


Fig.5.9 Polar plot of Gain and Directivity (Phi=0º)

Table.5.1 Comparison of various antenna parameters for different antenna designs

	With EBG Only	**With U-Slot Only**	**With EBG and U-Slot**
Directivity (dBi)	9.20703	9.83652	9.30497
Gain (dBi)	9.05105	9.65663	9.08584
Radiation Efficiency (%)	96.472	95.9426	95.0796
Bandwidth (%)	9.26	16.66	38.53

5.2 MEASRUED RESULTS

The antenna design with the presence of U-Slot structure on the patch and the EBG structure on the ground was the best design as it gave the best results overall. So only this design was fabricated. After fabrication the result were measured using the available instruments. The measured results are as follows.

The return loss of the antenna was measured using Keysight Technologies RF Analyzer model number N9914A as shown in fig.5.10. We can see the wide band in the measured results.

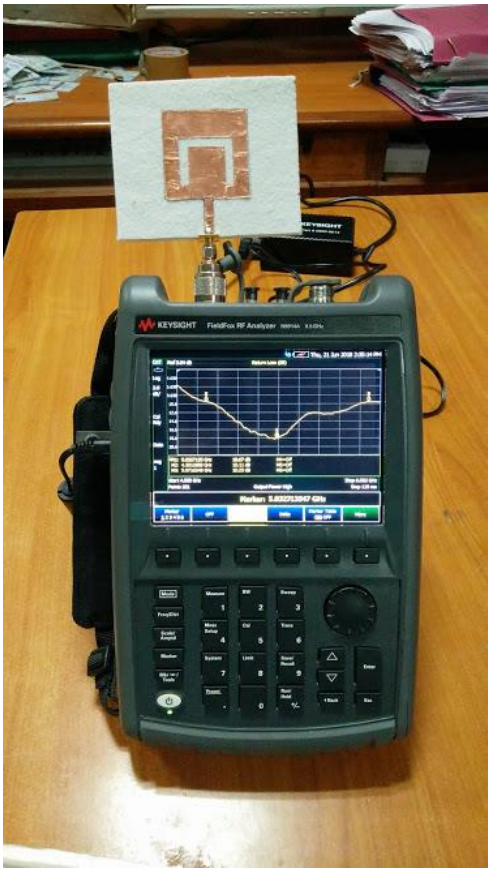


Fig.5.10 Measured result of S11 parameter

To observe the effect of the body we also measured the return loss in presence of the body, by placing the hand just below the antenna ground, as if it were to be attached to the hand. The results observed in the presence of the body were also quite impressive as the return loss increased further. But a slight decrease in the bandwidth is observed, as shown in fig.5.11.

Fig.5.11 Measured result of S11 parameter in the presence of body

5.3 COMPARISONS

A comparison is made between the simulated and fabricated results to further observe the difference between the two in fig.5.12. As we can observe the results are almost in agreement. Some frequency shift may be due to the fabrication errors or even the flexibility of the antenna.

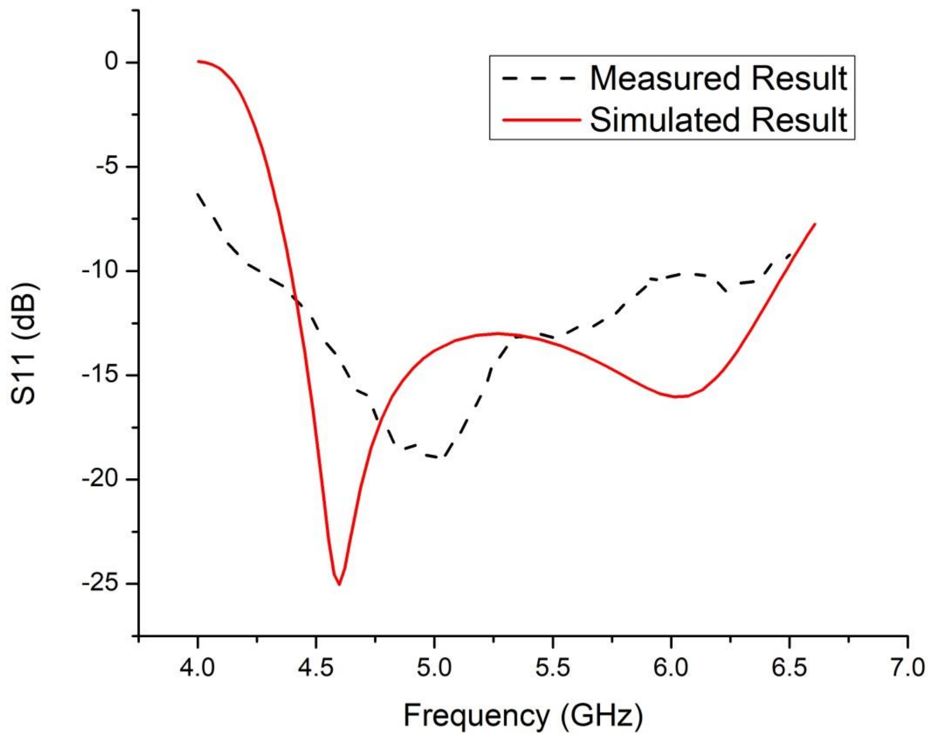


Fig.5.12 Comparison between simulated and measured S11 parameter

It is also important to observe the effect of the body on a wearable antenna. So a comparison is made for the S11 parameter in the presence and absence of body (hand). As we can observe in fig.5.13 the bandwidth has decreased slightly and the return loss has improved.

A comparison between the simulated and measured results with and without the presence of the body (hand) has been further made in table.5.2.

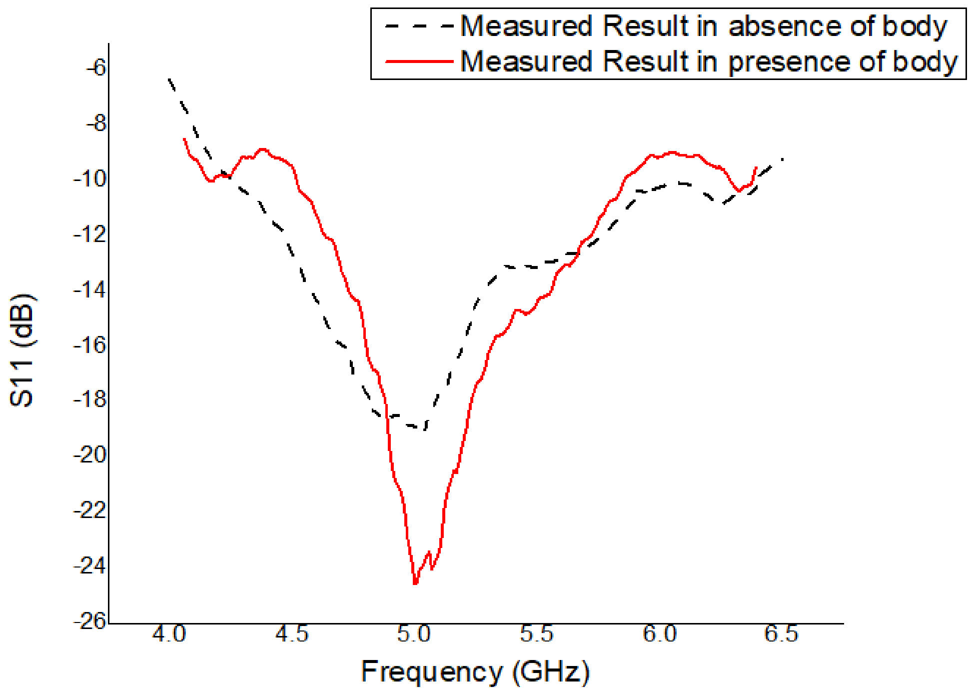


Fig.5.13 Comparison between measured S11 parameter with and without the presence of body

Table.5.2 Comparison between simulated and measured results

	Simulated Result	**Measured Result in absence of body**	**Measured Result in presence of body**
S11 (dB)	-25	-18.78	-24.55
Bandwidth (%)	38.53	35.2	32

5.4 CONCLUSION

The essential objective of this project was to design and fabricate a wearable wideband antenna. Many designs were considered before finalizing the design with a U-Slot on the patch and hexagonal EBG on the ground of the antenna. U-slot has the property to improve the bandwidth of the antenna by introducing a capacitive component in the input impedance which cancels the inductive component of the feed. EBG structures have the property to suppress the surface waves due to the high impedance introduced by the periodic structures. This leads to better gain, bandwidth and radiation efficiency. Additionally, it shields the body from the back radiations thus being beneficial for the wearable applications.

Material selection also played a major role as the antenna has to be flexible and robust. So felt was chosen as the substrate due its wide availability in various thicknesses and copper tape was selected as a conductor due to its availability and ease of fabrication. The patterns were cut out from the copper tape and pasted on the felt and SMA connector was connected.

Then the various parameters were measured and compared to the simulated results. Both the results are almost in agreement. Therefore, we have achieved the objective of design and fabrication of a wearable antenna with a U-slot patch and hexagonal EBG ground. Given its range of frequency, this antenna finds its applications in the WLAN band.

5.4.1 Future Work

Every research has some scope for its improvement. In this thesis, numerous features of wearable antennas were discussed. However, there are still some areas which can be improved and need more research. Wearable application is a continuously evolving field, so wearable antennas will continue to be in the scope of the research. Irrespective of the application few requirements like miniaturization, conformability, better radiation characteristics and SAR reduction will always be the aim in this research.

1. The copper tape used as the conductor in the fabrication of the antenna is not very dependable. The tape peels off or breaks due to bending or careless handling. Therefore making the antenna less durable or temporary. To avoid this, the new printable technology like Inkjet or 3D printing can be used. In these technologies the conductive links are printed in the required patterns directly onto the substrate. Or we can use the flexible yarned conductors, but they are not easily available.
2. It will always be an aim to achieve a better performance of the antenna. For that human errors during the fabrication process need to be avoided or at least

minimized. Hence, the fabrication field needs more development so that we get accurate results.

3. Prolonged exposure to the radiations in harmful for the body, so SAR reduction always has scope to be reduced. Effect of the antenna on the body should always be examined meticulously.
4. Material selection plays a vital role in the performance and reliability of the antenna. More research needs to be done on the materials to be used for these applications. Factors like availability, flexibility, conductivity, permittivity, thickness need special focus.
5. The most commonly used feeding is metallic SMA connector is used, but they are large and heavy, so small and lightweight connectors can be suggested in future for a low profile wearable antenna.
6. Conventional soldering is not that reliable on the fabrics as is can burn the fabric and the connections is very fragile. So new techniques could improve the fabrication process.
7. For robust and reliable wearable antenna, its performance has to be monitored in various harsh weather conditions. So the effect of water or wind or dirt needs to be researched. Waterproof materials can be focused on for the future.

REFERENCES

[1] "“IEEE 802.15 WPAN™Task Group 6 (TG6) Body Area Networks,” p. 1 [Online].," 2014. [Online]. Available: http://www.ieee802.org/15/pub/TG6.html.

[2] W.Scanlon, "Narrow band channel characterization & system issues for body-centric," in *European School of Antennas*, 2009.

[3] P. S. Hall and Y. Hao, Antennas and Propagation for Body-CentricWireless Communications, Norwood, USA: Artech House, 2012.

[4] D.Manteuffel, M. Grimmand, *Antennas and Propagation for On-, Off- In-Body Communications*, R. S. Toma, Ed. InTech, 2013.

[5] R.Chandra, "Antennas, wave propagation, and localization in wireless body area networks," Lund University, Lund, Sweden, 2014.

[6] M.S.Wegmuller, "Intra-body communication for biomedical sensor networks," Swiss Federal Institute of Technology, Zurich, Switzerland, 2007.

[7] H. Higgins, M. Yuce, J. Khan, *Implanted Wireless Communication Making a Real Difference*, Eds. Pan Stanford, 2012.

[8] P. Salonen, L. Sydanheimo, M. Keskilammi and M. Kivikoski, "A small planar inverted-F antenna for wearabla applications," *Wearable Computers, Digest of Papers, Third International Symposium*, pp. 95-100, 1999.

[9] J. G. Santas, A. Alomainy and Y. Hao, "Textile Antennas for On-Body Communications: Techniques and Properties," in *Antennas and Propagation, EuCAP, Second European Conference*, 2007.

[10] 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," *IEEE Transactions on Instrumentation and Measurement* , vol. 59, no. 12, Dec 2010.

[11] M.S.Shakhirul, M. Jusoh, A. H. Ismail, M. R. Kamarudin, R. Yahya, M.N.M.Yasin and T.Sabapathy, "1.575 GHz Circular Polarization Wearable Antenna with Three Different Substrate Materials," in *IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, Johor, Malaysia, Dec 2014.

[12] P.Salonen, Y.Rahmat-Samii, H.Hurme and M.Kivikoski, "Dual Band Wearable Textile Antenna," *IEEE Antenna and Propogation Society Symposium Digest held in conjunction with USNC/URSI National Radio Science Meeting,* pp. 463-466, 2004.

[13] K.-F. Tong, K.-M. Luk, K.-F. Lee and R. Q. Lee, "A Broad-Band U-Slot Rectangular Patch Antenna on a Microwave Substrate," *IEEE Transactions on Antennas and Propagation,* vol. 48, no. 6, June 2000.

[14] D. Sievenpiper, L. Zhang, R. F. J. Broas, N. G. Alexopolous and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and Techniques* , vol. 47, pp. 2059-2074, 1999.

[15] F. Yang and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," *IEEE Transactions on Antennas and Propagation,* vol. 51, pp. 2691-2703, 2003.

[16] F. R. Yang, R. Coccioli, Y. Qian and T. Itoh, "PBG-assisted gain enhancement of patch antennas on high-dielectric constant substrate," *Antennas and Propagation Society International Symposium IEEE,* vol. 3, pp. 1920-1923, 1999.

[17] P. Salonen, M. Keskilammi and L. Sydanheimo, "A low-cost 2.45 GHz photonic band-gap patch antenna for wearable systems," in *Eleventh International Conference on Antennas and Propagation (IEE Conf. Publ. no. 480), vol. 2, pp. 719-723* , 2001.

[18] *IEEE Standard Definitions of Term for Antennas, IEEE Standard 145,* Piscataway, NJ: IEEE: 445-199 Hoes Lane, 1993.

[19] C. A. Balanis, Antenna Theory: Analysis and Design, 3rd ed., John Wiley & Sons, Inc. 2005.

[20] D. Pozar, Microwave Engineering, USA: Addison-Wesley Publishing Company, 1990.

[21] J. Kraus, Antennas for All Applications, 3rd Edition, USA: McGraw-Hill, 2002.

[22] D. M. Pozar and D. H. Schaubert, "Microstrip Antenna: The analysis and design of Microstrip antenna and arrays," *IEEE Antennas and Propagation Society, Willey–Default,* 1995.

[23] D. Psychoudakis, G. Lee, C. Chen and J. Volakis, "Military UHF body-worn antennas for armored vests," in *Proceedings of the 6th European Conference on*

Antennas and Propagation (EuCAP). IEEE, 2010.

[24] Z. Popovic, P.Momenroodaki and R. Scheeler, "Toward wearable wireless thermometers for internal body temperature measurements," *IEEE Communications Magazine*, vol. 52, no. 10, p. 118–125, October 2014.

[25] F. Axisa, P. Schmitt, C. Gehin, G. Delhomme, E. McAdams and A. Dittmar, "Flexible technologies and smart clothing for citizen medicine, home healthcare, and disease prevention," *IEEE Transactions on Information Technology in Biomedicine*, vol. 9, no. 3, pp. 325-326, Sept 2005.

[26] S. Park and S. Jayaraman, "Enhancing the quality of life through wearable technology," *IEEE Engineering in Medicine and Biology Magazine*, vol. 22, no. 3, pp. 41-48, May 2003.

[27] S. Ullah, "Wireless body area network for ubiquitous health monitoring," 2010. [Online]. Available: http://www.koreaittimes.com/story/10133/wireless-body-area-network-ubiquitous-health-monitoring.

[28] "Running GPS Watches," Tomtom, 2014. [Online]. Available: http://sports.tomtom.com/en_us/.

[29] "Micoach," Adidas, 2018. [Online]. Available: http://micoach.adidas.com/.

[30] R. Salvado, C. Loss, R. Gonçalves and P. Pinho, "Textile materials for the design of wearable antennas: A survey, Sensors, vol. 12, no. 11, pp.," 2012. [Online]. Available: http://www.mdpi.com/1424-8220/12/11/15841.

[31] P. Salonen, Y. Rahmat-Samii, M. Schaffrath and M. Kivikoski, "Effect of textile materials on wearable antenna performance: a case study of GPS antennas," *IEEE Antennas and Propagation Society International Symposium*, vol. 1, p. 459–462, June 2004.

[32] P. Salonen, Y. Rahmat-Samii, M. Schaffrath and M. Kivikoski, "Effect of conductive material on wearable antenna performance: a case study of WLAN antennas," *IEEE Antennas and Propagation Society International Symposium*, vol. 1, p. 455–458, June 2004.

[33] T. Kaija, J. Lilja and P. Salonen, "Exposing textile antennas for harsh environment," in *Military Communications Conference (MILCOM 2010)*, Oct 2010.

[34] Y. Ouyang and W. Chappell, "High Frequency Properties of Electro-Textiles for Wearable Antenna Applications," *IEEE Transactions on Antennas and*

Propagation, vol. 56, no. 2, p. 381–389, Feb 2008.

[35] Q. Bai and R. Langley, "Bending of a small coplanar textile antenna," in *Loughborough Antennas and Propagation Conference (LAPC)*, Nov 2010.

[36] I. Locher, M. Klemm, T. Kirstein and G. Troster, "Design and Characterization of Purely Textile Patch Antennas," *IEEE Transactions on Advanced Packaging,* vol. 29, no. 4, pp. 777-778, Nov 2006.

[37] J.Matthews and G. Pettitt, "Development of flexible, wearable antennas," in *Proceedings of the 3rd European Conference on Antennas and Propagation (EuCAP)*, March 2009.

[38] T. Maleszka and P. Kabacik, "Bandwidth properties of embroidered loop antenna for wearable applications," in *Proceedings of the 3rd European Wireless Technology Conference*, Paris, France, 27–28 September 2010.

[39] W. Whittow, *Embroidery and related manufacturing techniques for wearable antennas: Challenges and opportunities,* 2014.

[40] A. Chauraya, S. Zhang, W. Whittow, T. Acti, R. Seager, T. Dias and Y. Vardaxoglou, "Addressing the challenges of fabricating microwave antennas using conductive threads," in *Proceedings of 6th European Conference on Antennas and Propagation, EuCAP*, 2012.

[41] K. Technologies, "Advanced Design System 2016.1". USA 1995 - 2018.

[42] K.-F. Tong, K.-M. Luk, K.-F. Lee and R. Q. Lee, "A Broad-Band U-Slot Rectangular Patch Antenna on a Microwave Substrate," *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION,* vol. 48, no. 6, June 2000.

[43] K. Lee, K.M.Luk, K. F. Tong, S.M.Shum, T.Huynh and R.Q.Lee, "Experimental and simulation studies of the coaxially fed U-slot rectangular patch antenna," *IEEE Proceedings - Microwave Antennas Propagation,* vol. 144, no. 5, Oct 1997.

[44] T. Huynh and K. F. Lee, "Single-layer single-patch wideband microstrip antenna," *Electron. Lett.*, vol. 31, no. 16, p. 1310–1312, Aug. 3, 1995.

[45] Y. L. Chow and K. H. Shiu, "A theory on the broadbanding of a patch antenna," *Asia-Pacific Microwave Conference Proceedings,* vol. 1, pp. 245-248, 1997.

[46] F. Yang and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," *IEEE Transactions on Antennas and Propagation,* vol. 51, pp. 2691-2703, 2003.

[47] F. R. Yang, R. Coccioli, Y. Qian and T. Itoh, "PBG-assisted gain enhancement of patch antennas on high-dielectric constant substrate," *Antennas and Propagation Society International Symposium IEEE*, vol. 3, pp. 1920-1923, 1999.

[48] J. A. Ansari and R. B. Ram, "Broadband Stacked U-Slot Microstrip," *Progress In Electromagnetics Research Letters*, vol. 4, pp. 17-24, 2008.

[49] P. Baccarelli, P. Burghignoli, F. Rezza, A. Galli, P. Lampariello, S. Paarulotto and G. Valerio, " Dispersive Analysis of Wide-Bandstop Compact EBG Microstrip Lines for Filter Applications," in *ISMOT*, 2007.