Design of Wearable Antenna System on Different Materials & Their Performance Analysis at the Off and On Body Environment in terms of Impedance Matching and Radiation Characteristics

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Abstract- This paper aims to design textile microstrip patch antennas on three different high performance fabric materials as substrates and a conventional patch antenna on FR-4 (PCB) substrate, imposed on human body environment for wireless body area network (WBAN) applications. It also compares the performance of the designed antennas at the on and off body environment. These antennas operate on ISM 2.45 GHz frequency band. Electro textile materials, Panama fabric (ε_r= 2.12), Fleece (ε_r =2.22) and Dacron fabric (ε_r =3) as well as PCB material (ε_r =4.3) are used as the antenna substrates. A human body model having three layers (skin, fat and muscle) is then developed and the antennas are applied on this body model to investigate their characteristics and performance and also the impact of human body layers on these antennas.

Keywords- Textile Antenna, Microstrip patch, Narrow Band, Human body model and Electro-textile material.

1 INTRODUCTION

Body area networks (BAN) are a Natural progression from the personal area network (PAN). This network enables wearable computer devices to interact with each other and exchange digital information using the electrical conductivity of the human body as a data network [1]. With the recent development of wireless communication technology, many researchers pay great attention to the study of Wireless Body Area Networks (WBAN). The application of WBAN has been expanding in medical services, national defense, wearable computing and so forth. [2] Several frequency bands have been assigned for WBAN systems, such as medical implant communication system (MICS: 400 MHz) band, the Industrial Scientific Medical (ISM: 2.45 GHz and 5.8 GHz) band and the Ultra Wide band (UWB: 3.1-10.6 GHz). [3]

There will be no effective wireless communication between two entities without antenna. Antenna brings the whole wireless world together. Wearable intelligent textile system is an innovative fast growing field in application oriented field [4].The textile antenna is a fundamental part of wireless body area networks. Enhancement in communication and electronic technology has enabled the development of compact and intelligent antenna devices which can be positioned on the human body or implanted inside it [5]. Such body wearable antennas should be hidden and unobtrusive [6]. Miniaturization in microelectronics along with other technologies allows these antennas to integrate into clothing paving the way to the development of wearable wireless devices. The textile antenna system can be used for a wide variety of applications including solution for real time physiological measurements systems, pulse rate monitoring in sports, and navigation support in the car and so on. They can also be used to keep continuous record of wearer's health by monitoring their vital signs. Textile antennas also assist the emergency services such as fire fighters, detective and police [7]. It also helps to establish communication between the soldiers and other units of the modern battle field including unmanned aerial vehicles [6]. The electro-textile materials have also been used for the development of WiBro (also called mobile WiMax) antennas. [8] In this paper, textile antennas are integrated fully into the garments to preserve flexibility and comfort. These antennas have a flat, planar structure to be comfortably worn. These antennas do not disturb the movement of the wearer since it is light weight and flexible. The radiation efficiency, cost effectiveness, ease of system integration and immunity to performance degradation are also the factors to consider while designing these antennas. Four microstrip patch antennas are designed here for operating at the narrow band (ISM) WBAN at the frequency level of 2.45 GHz for short range communication. Here four different substrates with different permittivity ε_r (2.12, 2.22, 3 and 4.3) are used. In case of wearable antennas their performance varies when they are placed on human body. This paper mainly focuses to evaluate the designed antenna's performance on human body. This phenomenon is achieved by creating three significant layers of human body which includes skin, fat and muscle. Originality of this work is-the antennas are designed on different textile and non textile materials and all of them resonate at about ISM 2.45 GHz frequency for planar structure irrespective of off or on body environment. This paper also compares the performance and characteristics of the designed antennas at both the on and off body area in terms of radiation properties and impedance matching. The structures are designed and analyzed using CST Microwave Studio software package.

2 SUBSTRATE MATERIALS SELECTION

The permittivity of a material is usually given relative to that of free space which is known as relative permittivity or dielectric constant; ε_r. Different substrates having different dielectric constants affect the antenna performance in various ways. Here, Dacron fabric with ε_r =3, Fleece fabric with ε_r =2.22, Panama fabric with ε_r =2.12 and FR-4 with ε_r =4.3 are used as antenna substrates. [9] Selection of material for designing the antenna is unique in this paper. Panama fabric is excellent in clothing, absorbency, durability, and resilience. It is less flammable too. Properties of the fleece material is pleasant to touch, very warm and provides warmth without weighing a lot, dries fast, never loses its properties during use, looks attractive, and very good hygroscopic. On the other hand Dacron fabric includes high tensile strength, high resistance to stretching, durability and outstanding electrical property whereas FR-4 is the primary insulating backbone upon which the vast majority of rigid printed circuit boards (PCBs) are produced. It is a composite material composed of woven fibreglass cloth with an epoxy resin binder that is flame resistant. [10] The patches are made of copper threads which are perfect electrical conductors (PEC).

3 ANTENNA DESIGN AND IMPLEMENATION

The Microstrip Patch Antennas are designed to operate at 2.45 GHz. The patch ground plane is attached on the back of the substrate with the same dimensions of it. The antenna is fed through a transmission line via a quarter wavelength section to match the impedance at 50 ohms.

TABLE I
MICROSTRIP PATCH ANTENNA MEASUREMENTS FOR DESIGNING

Parameter (mm)	**Dielectric Constant, ε_r = 2.12 (Panama fabric)**	**Dielectric Constant, ε_r = 2.22 (Fleece)**	**Dielectric Constant, ε_r =3 (Dacron)**	**Dielectric Constant, ε_r =4.3 (FR-4)**
Patch Length (L)	42	39	34	28.7
Patch Width (W)	50	58	44	42
Substrate Length (L)	90	90	80	74
Substrate Width (W)	80	80	60	60
Substrate Thickness (h)	1.6	1.524	1.524	1.524
Feed Width(W)	5.089	4.5	3.8	3.8

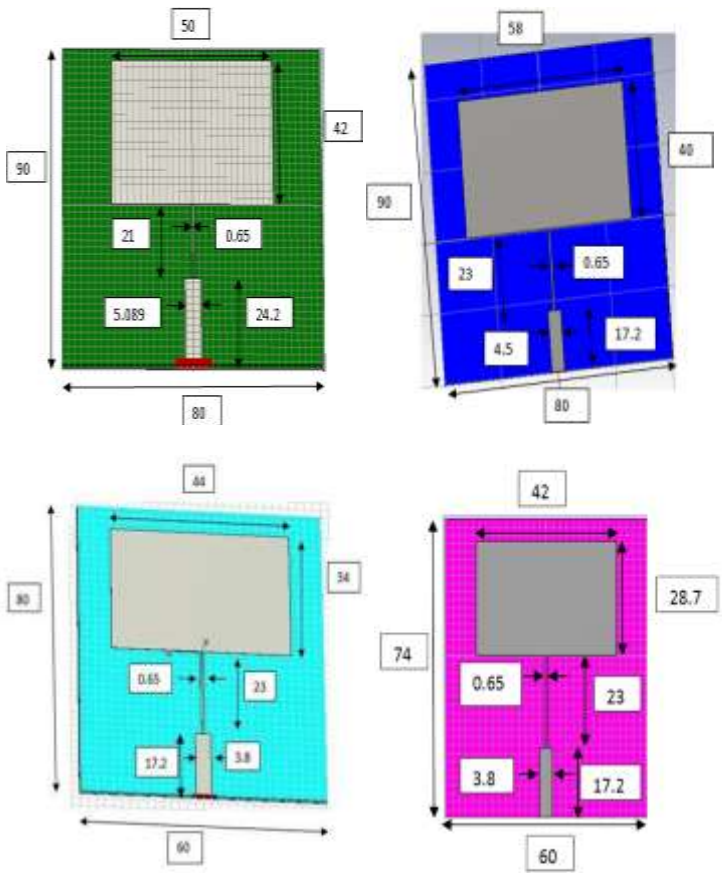


Fig. 1 Microstrip patch antenna for substrate permittivity, ε_r=2.12, 2.22, 3, 4.3 accordingly

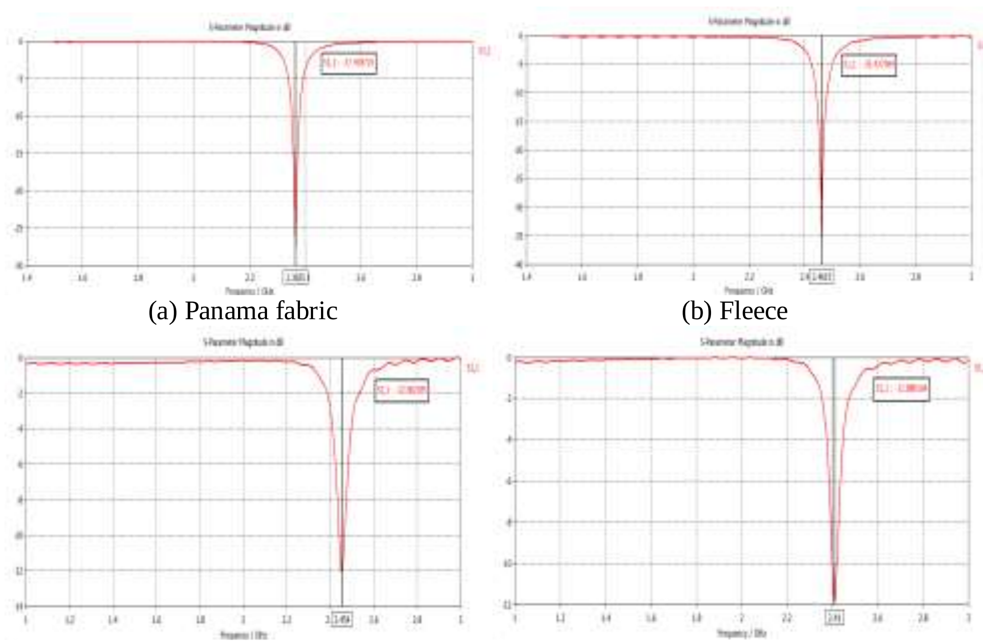
4 PERFORMANCE ANALYSIS OF PLANAR MICROSTRIP PATCH ANETENNA

The performance parameters for antennas with different substrate materials are summarized below:

Table-II
Characteristics Comparison for Antennas with Different Substrate Materials

Parameters	**Panama fabric (ε_r=2.12)**	**Fleece(ε_r=2.22)**	**Dacron (ε_r=3)**	**FR-4 (ε_r=4.3)**
Frequency (GHz)	2.365	2.4615	2.454	2.41
S Parameter (dB)	-27.438725	-35.437584	-12.082185	-11.880164
Maximum Surface Current (A/m)	41.532	39.6632	50.7757	56.3248

4.1. S-parameter analysis of planar micro strip patch antenna with different substrate permittivity



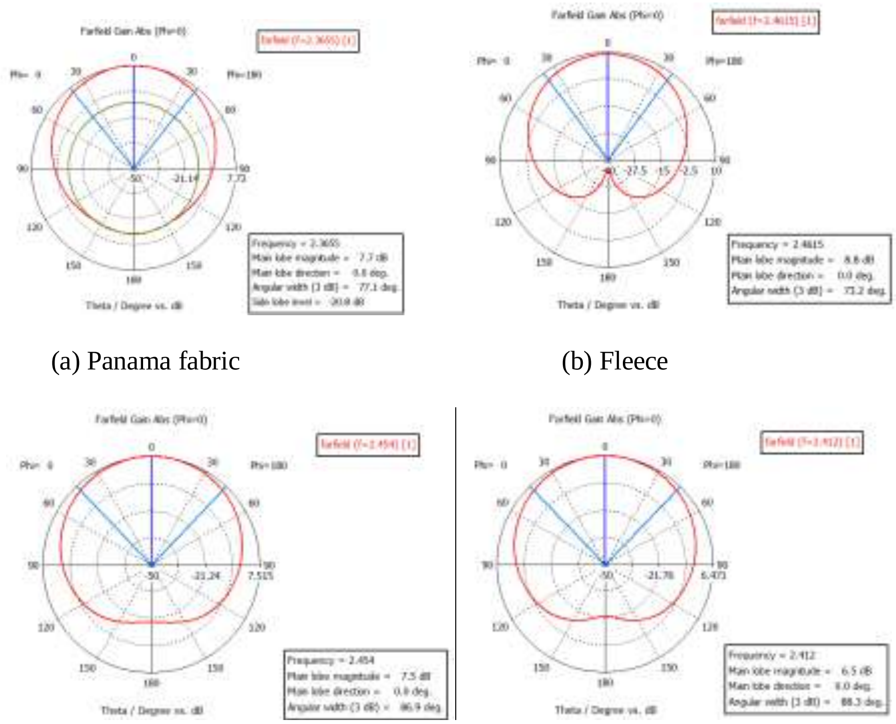
(a) Panama fabric (b) Fleece

(c) Dacron (d) FR-4 (PCB)

Fig.2. Simulated S-parameter results comparison for planar antenna

The S-parameter demonstrates a good impedance matching with a return loss of -27.43 dB at resonance frequency 2.365 GHz for panama fabric substrate. For Dacron fabric the resonance frequency is 2.454 GHz with a return loss of -12.08 dB. The impedance matching is quite poor in case of FR-4 (PCB) substrate with a return loss of -11.88 dB which resonates at 2.41 GHz. The fleece fabric substrate exhibits a good impedance matching with a return loss of -35.43 dB at resonance frequency 2.4615 GHz which is the best among all four. Here, it is evident that the return loss of the hard PCB substrate is higher compared to that of the textile materials. This indicates that the performance of the textile materials is better on the antenna perspective.

4.2. Radiation pattern analysis of planar micro strip patch antenna with different substrate permittivity



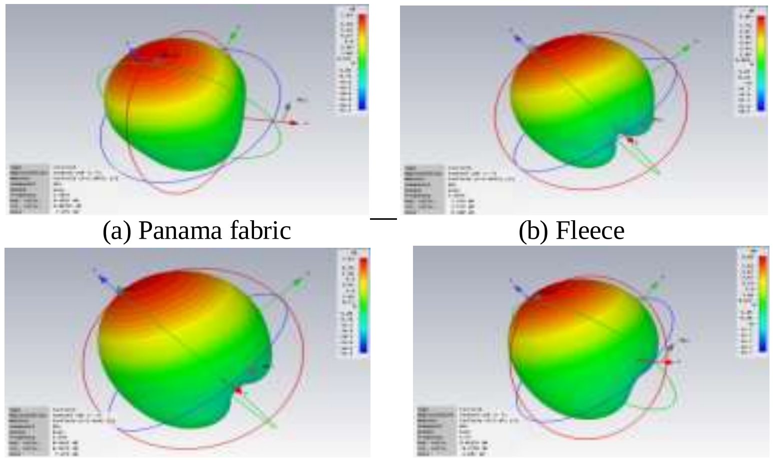
(a) Panama fabric (b) Fleece

(c) Dacron (d) FR-4 (PCB)

Fig.3. Comparison of Radiation pattern for planar Microstrip Patch antenna

Fig. 3 shows that power is radiated mostly in the upper hemisphere; the power beam is directed towards 0 degree with a main lobe magnitude of around 6.5 to 9 dB for all the cases. The pattern with substrate material Fleece fabric has a main lobe of 8.8 dB (portrayed in fig. 3(b)) which is the best among all the patterns. The fleece fabric also exhibits a reduced side lobe level which demonstrates its proficiency over all the antennas with other substrates. At 3 dB (half power) level, the angular width of this antenna is 73.2 degree. Fig.3 (a) shows the elevation pattern for panama fabric at 2.365 GHz frequency; the power beam is directed towards 0 degree with a magnitude of 7.7 dB where the half power beam width is 77.1 degree. The side lobe level of the radiation is -20 dB which depicts that the power at the back of the antenna is quite high. 3(c) shows the elevation pattern for Dacron fabric at 2.454 GHz which demonstrates a similar main lobe as that of the panama fabric with substrate permittivity ε_r =2.12. In this case, the magnitude is 7.5 dB with a half power beam width of 86.9 degree which is much higher compared to those of the other textile materials. Fig 3(d) is the elevation pattern for the PCB material whose main lobe magnitude is the lowest compared to that of the textile materials discussed so far. At 2.41 GHz the magnitude is a mere 6.5 dB, however, at 3 dB the angular width is 88.3 degree which is quite similar to that of the antenna with Dacron fabric.

4.3. 3D radiation pattern analysis of planar micro strip patch antenna with different substrate permittivity



(a) Panama fabric (b) Fleece

(c) Dacron (d) FR-4 (PCB)

Fig.4. Comparison of 3D Radiation pattern for planar Microstrip Patch antenna

Table-III

Radiation Characteristics Comparison for Antennas with Different Substrates

Parameters	**Panama(ε_r=2.12)**	**Fleece (ε_r=2.22)**	**Dacron (ε_r=3)**	**FR-4 (ε_r=4.3)**
Gain (dB)	7.931	9.488	7.812	6.895
Directivity (dB)	7.829	8.214	7.247	6.882
Total Efficiency	1.022	1.341	1.069	0.9378

Fig. 4 shows the 3D directional radiation pattern of the narrowband planar microstrip patch antenna on different substrates. The antenna with fleece fabric exhibits the highest gain of 9.488 dB whereas the Dacron fabric and panama fabric substrates show similar directive radiation patterns with gains 7.812 dB and 7.931 dB respectively. The non- textile PCB material has the lowest gain of 6.895 dB with the lowest total efficiency of 0.9378 (depicted in table 2). The total efficiency of panama fabric and Dacron are quite similar whereas fleece exhibits the highest efficiency with a magnitude of 1.341 on a linear scale. The table 2 also represents the directivity of the antennas which follows the similar trend of the gain. These radiation characteristics are completely compatible with the s-parameter characteristics of the antennas which are evident from the earlier discussions depicted in section 4.1.

5 PERFORMANCE ANALYSIS OF MICROSTRIP PATCH ANTENNA ON HUMAN BODY

Microstrip antennas provide better performance compared to the other antennas at the on-body environment. In fact the ground plane of these antennas reduces the energy absorption by body and this can increase the efficiency. [11] A Three-layer model (dry skin, fat, muscle) is adopted to model the human body in the CST environment. This layered model can quite well represent most of the body regions, since the fat has similar properties to the bone tissue, and the electrical parameters of the muscle and many inner organs are alike. [12] Since the human body tissues are frequency dispersive materials, the dielectric properties of such tissues are calculated specifically for 2.45 GHz.

<u>Table-IV</u>
<u>Parameters for human body model</u>

Tissue name	Frequency [GHz]	Conductivity [S/m]	Relative permittivity	Wavelength [m]	Thickness [mm]
Dry Skin	2.45	1.464	38.007	0.019657	1
Fat	2.45	0.10452	5.2801	0.053113	5
Muscle	2.45	1.7388	52.729	0.016731	20

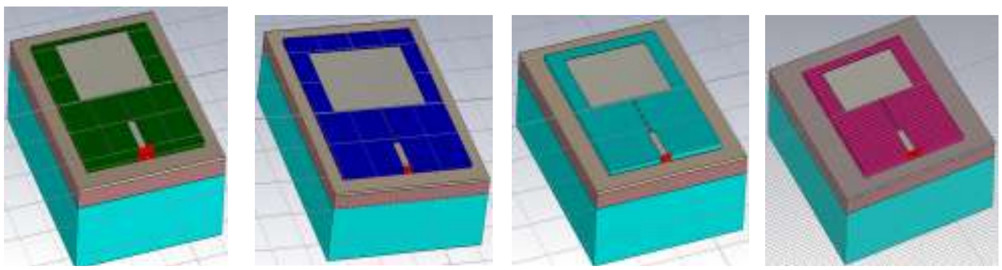
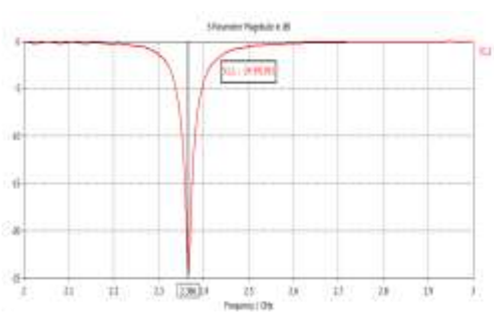


Fig. 5. Microstrip patch antenna on human body layers for substrate permittivity (εr= 2.12, 2.22, 3 and 4.3)

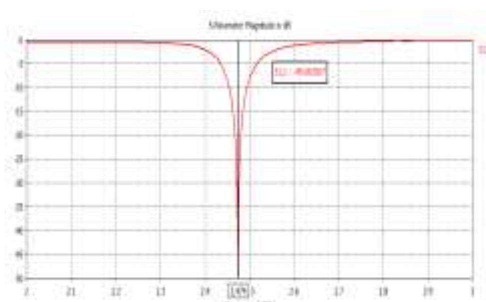
<u>Table-V</u>
<u>Characteristics Comparison for Antennas with Different Substrate Materials on Human Body</u>

Parameters	**Panama fabric (ε_r=2.12)**	**Fleece (ε_r=2.22)**	**Dacron (ε_r=3)**	**PCB(ε_r=4.3)**
Frequency (GHz)	2.366	2.474	2.455	2.412
S Parameter (dB)	-24.591393	-49.602657	-19.460302	-18.608961
Maximum Surface Current (A/m)	34.7531	36.5985	46.8503	51.3282

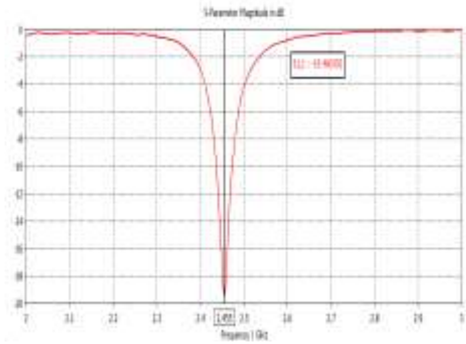
5.1. S-parameter analysis of planar micro strip patch antenna with different substrate permittivity on human body



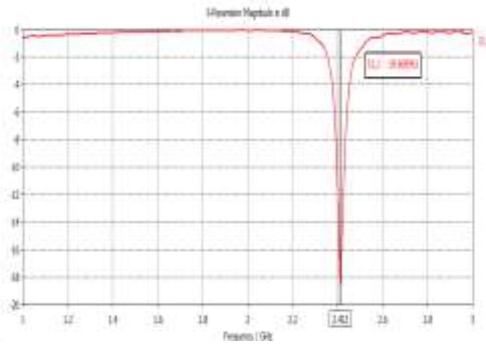
(a) Panama fabric



(b) Fleece



(c) Dacron

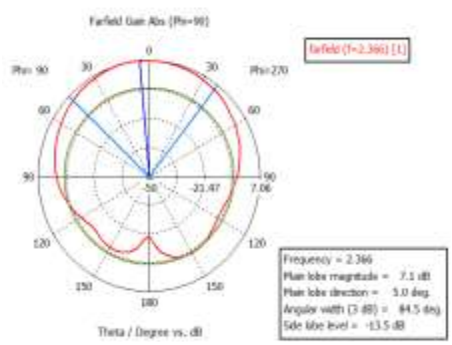


(d) FR-4 (PCB)

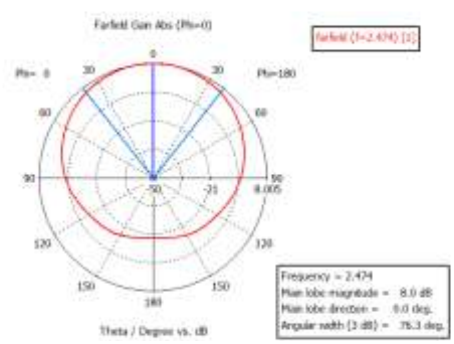
Fig. 6. Simulated S-parameter results comparison for microstrip patch antenna on human body

Fig. 6 illustrates the return losses for the same antennas on top of a human body model. For panama fabric substrate, the S-parameter demonstrates a good impedance matching with a return loss of -24.59 dB at the resonance frequency of 2.366 GHz which is evident from fig. 6(a). Fig. 6(c) shows that the antenna with Dacron fabric has a resonance frequency of 2.455 GHz with a return loss of -19.46 dB. The impedance matching for FR-4 (PCB) substrate is still poor compared to that of the other materials which is apparent from the return loss of -18.60 dB with an operating frequency of 2.412 GHz. The antenna with fleece fabric substrate again exhibits the best impedance matching among all the materials with a return loss of -49.60 dB at resonance frequency 2.474 GHz. Here, it is evident that even at the on body environment, the return loss of the non-textile PCB substrate is higher compared to that of the textile materials.

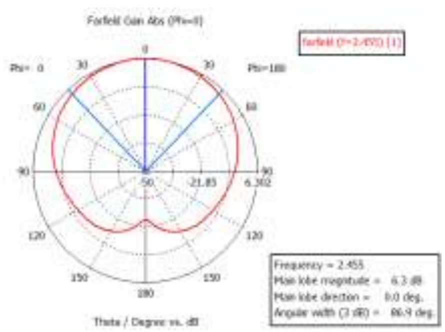
5.2. Radiation pattern analysis of micro strip patch antenna with different substrate permittivity on human body



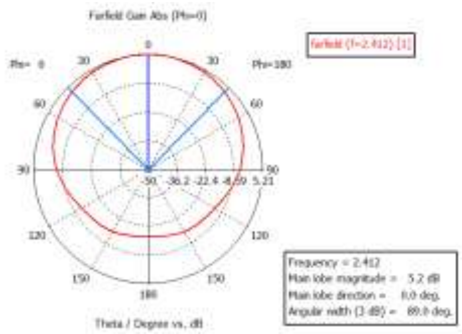
(a) Panama fabric



(b) Fleece



(c) Dacron

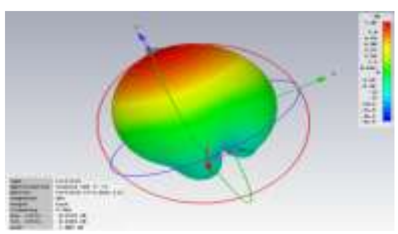


(d) FR-4 (PCB)

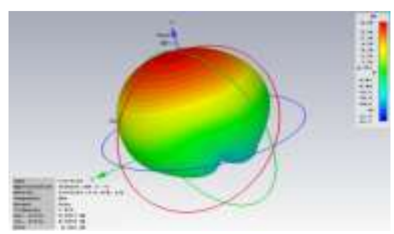
Fig.7. Comparison of Radiation pattern for Microstrip Patch antenna on human body

Fig. 7 shows the elevation pattern for the antennas with different substrates on human body model. The main power beam is directed towards 0 degree with a main lobe magnitude of around 5.2 to 8 dB in all the cases. The pattern with substrate material Fleece fabric has a main lobe of 8 dB (portrayed in fig. 7(b)) which is the best among all the patterns. At 3 dB (half power) level, the angular width of this antenna is 76.3 degree. Fig.7 (a) shows the elevation pattern for panama fabric at 2.366 GHz frequency; the power beam is directed towards 0 degree with a magnitude of 7.1 dB where the half power beam width is 84.5 degree. The side lobe level of the radiation is -13.5 dB which depicts that the power at the back of the antenna is high enough. 7(c) shows the elevation pattern for Dacron fabric at 2.455 GHz which demonstrates that at on body environment the main lobe magnitude gets reduced compared to that of the panama fabric with substrate permittivity ε_r =2.12. In this case, the magnitude is 6.3 dB with a half power beam width of 86.9 degree. For PCB material the main lobe magnitude is the lowest compared to that of the textile materials with a value of 5.2 dB (depicted in fig. 7 (d)). The operating frequency in this case is 2.412 GHz and the half power beam-width is 89 degree.

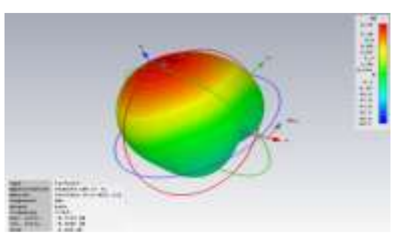
5.3. 3D radiation pattern analysis of micro strip patch antenna with different substrate permittivity on human body



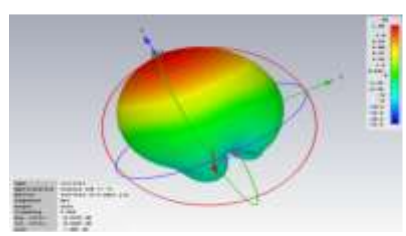
(a) Panama fabric



(b) Fleece



(c) Dacron



(d) PCB

Fig.8. Comparison of 3D Radiation pattern for Microstrip Patch antenna on human body

Table-VI
Radiation Characteristics Comparison for Antennas with Different Substrates on human body

Parameters	**Panama fabric (ε_r=2.12)**	**Fleece (ε_r=2.22)**	**Dacron (ε_r=3)**	**FR-4 (ε_r=4.3)**
Gain (dB)	7.089	8.262	6.310	5.281
Directivity (dB)	7.442	7.681	6.422	6.081
Total Efficiency	0.9187	1.143	0.9637	0.8204

Fig. 8 shows the 3D directional radiation pattern of the planar micro strip patch antenna with different substrates at human body environment. The antenna with fleece fabric exhibits the highest gain of 8.262 dB as it has the best impedance matching with a return loss of -49.60dB. The Dacron fabric and panama fabric substrates show similar directive radiation patterns with gains 6.310 dB and 7.089 dB respectively. The non- textile PCB material has the lowest gain of 5.281 dB with the lowest total efficiency of 0.8204 (depicted in table VI). The total efficiency of panama fabric and Dacron are quite similar whereas fleece exhibits the highest efficiency with a magnitude of 1.143 on a linear scale. The table VI also represents the directivity of the antennas which follows the similar trend of the gain. From the above discussion it is apparent that these radiation characteristics at the on body environment are also completely compatible with the s-parameter characteristics resembling the off-body environment.

6 COMPARISONS OF ANTENNA PARAMETERS AT OFF AND ON BODY ENVIROMENT

The simulated off body antenna parameters are compared here with those at the on body environment. To be more specific, the return loss and operating frequency, radiation pattern and the surface current for antennas with different materials are analyzed to investigate how the performance of these antennas are affected at the body area in comparison to free space.

6.1. Comparison of S-Parameter

A closer look at the table II and V reveals that the resonant frequency at the on body environment does not deviate much from that of the free space. The maximum deviation is observed for fleece fabric where the free space operating frequency 2.4615 GHz diverges to 2.474 GHz at the body area. The other textile materials panama fabric and dacron fabric shows almost no deviation at the human body environment. For on body environment, the resonace frequency for antennas with Panama fabric and Dacron Fabric is found at 2.366 GHz and 2.455 GHz respectively whereas the same antennas without the human body layers, resonate at 2.365 and 2.454 GHz respectively. The resonance frequency does not deviate even in case of the non textile material PCB which is evident from a mere variation of 2.41GHz to 2.412 GHz.

The Table II and V are again compared to have a better insight into magnitude of return losses of the antennas at on and off body environment. The return loss of antennas with fleece, dacron and PCB exhibits higher impedance matching at the body area in comparison to that of the free space.The fleece fabric antenna shows the highest impedance matching with a return loss of-35.437dB at the off body condition whereas on top of the human body tissue layers it reduces much further and reaches a value of -49.602657 dB. The antenna on dacron and PCB follow the same trend of the fleece at on body environment (--19.460302 dB) is lower than that at the free space (-12.082 dB). The non textile PCB has the lowest impedance matching at the free space with a return loss of -11.80164 dB which eventually reduces to -18.608961 dB at the human body environment resulting an improvement of impedance matching. The antenna on the panama fabric material behaves differenly in comparison to the other substrates. In this case,the return loss increases from a value of -27.438 dB (free space) to -24.591393 dB (body environment) unlike others, which reveals opposite characteristics of panama fabric.

6.2. Comparison of Radiation Pattern:

Table-VII
Comparison of radiation patterns at on and off body environment

Parameters		Panama fabric	Fleece	Dacron	FR-4 (PCB)
Main Lobe Magnitude	**Off Body**	7.7 dB	8.8 dB	7.5 dB	6.5 dB
	On Body	7.1 dB	8.0 dB	6.3 dB	5.2 dB
Gain	**Off Body**	7.931 dB	9.488 dB	7.812 dB	6.895 dB
	On Body	7.089 dB	8.262 dB	6.310 dB	5.281 dB
Total Efficiency	**Off Body**	1.022	1.341	1.069	0.9378
	On Body	0.9187	1.143	0.9637	0.8204

Table VII depicts the comparison of radiation pattern parameters at the free space with that of the body area.It can be observed that the main lobe magnitude is higher at the off body situation compared to the on body environment. The gain and efficiency also exhibit the same trend. These parameters comply with the s-parameter results of different materials which is evident from the fact that the fleece fabric has the highest main lobe magnitude, gain and efficiency while PCB has the lowest as like as the s-parameter results discussed in the earlier section. However, the radiation characteristics differs from the s-parameter results in the sense that in most of the cases an improved impedance matching is observed at the on body environment while the radiation characteristics are always poor at the body area in comparison to off body environment.

7 CONCLUSIONS

The aim of this paper is to observe the performance and characteristics of different antennas in free space and at human body environment for narrow band frequency (2.45GHz). The key finding of this paper lies in the fact that the radiation characteristics and performance of the antenna deteriorates at the body area environment. This is because of the lesser amount of current flow through the antenna patches due to the presence of highly dielectric human body tissue layers. In terms of performance and radiation properties, the textile materials turn out to be better than the non textiles. Among the textile fabrics; fleece has the best performance with the highest gain, main lobe magnitude and efficiency while these properties are quite poor in case of non textile PCB material. The panama fabric and Dacron fabric exhibit mediocre characteristics with performance better than PCB but worse than fleece. The similar tradition is followed in case of the impedance matching as well. Here, it can be noticed that the PCB material has the poorest impedance matching of all with a high return loss while Fleece shows a very good matching with panama fabric and Dacron being moderate. This ensures that a very small amount of power is reflected back to the transmitter in case of fleece antenna and a lot of power is reflected for antenna with PCB substrate. However, for all the materials apart from panama fabric the impedance matching seems to have improved at the on body environment. This helps us to reach a conclusion that for lower permittivity substrates; the impedance matching is higher at off body condition while as the permittivity of the substrate material increases; the return loss tends to reduce more at the on body environment revealing improved impedance matching at that condition. The frequency does not detune much for any of the antennas due to the presence of human body. This is due to the presence of a full ground plane at the back of the patch antenna. [13]. The overall result analysis shows that though both the textile and non textile materials can be used for designing antennas for Wireless Body Area Network (WBAN) applications, the textile antennas are most suitable compared to the antennas with non textile materials.

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