A Compact Hexagonal Slot Antenna For Wearable Applications

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Abstract- This paper presents a hexagonal slot antenna for wearable applications. The antenna is electromagnetically coupled with hexagonal parasitic patch and is powered through microstrip line feed structure. The proposed antenna is designed using textile substrates like Polyester, Jeans and Cotton. Textile antennas are more preferred for wearable applications due to their effective cost, low weight and low profile. The modeling and simulation is performed using Ansoft HFSS (High Frequency Structural Simulator) software. Antenna characteristics such as the return loss, VSWR, Gain, Radiation pattern are analyzed. Comparative results of simulations and measurements are presented. As the wearable antennas operate near the human body, it is important to measure the radiation absorbed by the human body. The EM radiation absorbed by human body is measured in terms of Specific absorption rate. Human hand phantom has been modeled to measure the specific absorption rate using CST-MWS.

Keywords - wearable antenna; hexagonal slot; textile substrate ; microstrip feed ; parasitic patch; specific absorption rate ; phantom model

I. INTRODUCTION

In recent years, body-centric wireless communication becomes an important part of fourth generation (4G) mobile communication systems. Body-centric communication takes place firmly within the sphere of personal area networks (PANs) and body area networks (BANs). The body-centric wireless communication can be categorized into on-body, off-body or in-body communication. The on-body communication provides the link between body mounted devices communicating wirelessly, while off-body communication defines the radio link between body worn devices and base units or mobile devices located in surrounding environment. Finally, in-body communication is a communication between wireless medical implants and on body nodes.

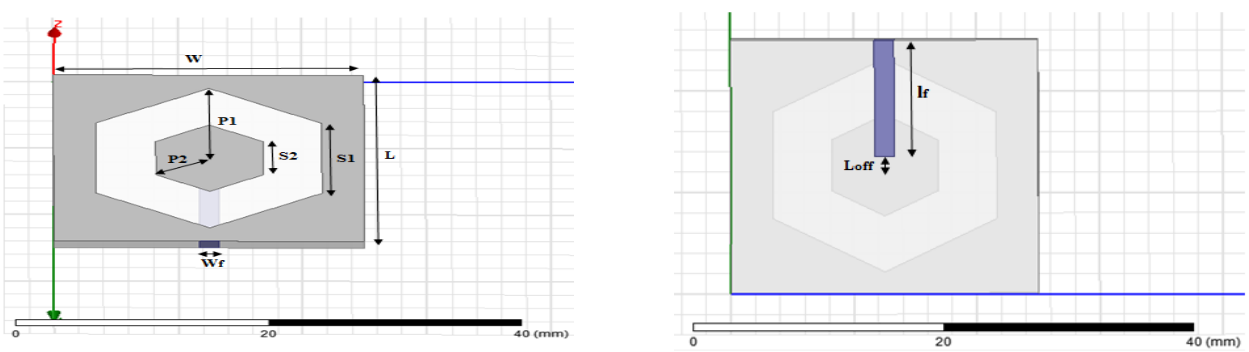
Wearable, fabric based antennas play an important role in wireless body centric communications. Commonly, wearable antenna requirements for all modern application require light weight, low cost, almost maintenance-free and no installation. There are number of fields that use body centric communication systems, such as paramedics, fire fighters, and military. Besides, wearable antennas also can be applied for youngsters, the aged, and athletes for the purpose of monitoring their vitals. The wearable antenna can be used to monitor the human physiological parameters such as Heart rate, Blood pressure, Respiratory rate, Respiratory volume and Body temperature. It can also be used to monitor the parameters such as Electrocardiogram (ECG), Galvanic Skin Response (GSR), Oxygen saturation in blood (SaO_2), Electromyogram (EMG), Electroencephalogram (EEG). Since wearable antennas operate in close proximity to the human body, the loading effect due to the lossy nature of body tissues coupled with their high dielectric constants and conductivity makes the design of a high radiation efficiency antenna challenging.

Owing to the advantages of low weight, low cost fabrication, low profile, and easy integration, small antennas such as microstrip antenna, RFID antenna, Fractal antenna, etc [1] have attracted much more attention for hand-held devices and other compact communication systems. It is suitable for body-worn applications because the ground plane protects the body tissues and radiates perpendicularly to the planar structure [2]. The printed slot antenna with a ground plane dimension of 110 x 110mm^2 and slot dimension of 53.7 x 53.7mm^2 gives the narrow bandwidth of 2GHz [3]. The printed E-shaped slot antenna with the slot dimension of about 40 x 45mm^2 yields wider impedance bandwidth of 120% and frequency range of 2.8-10.4GHz [4, 5]. At the time of fabrication, the large size antenna gives variations in the desired outputs. Printed cone antenna, elliptical slot antenna and other large size antenna like reflectors and horn antennas are not suitable for the wireless handheld devices [6].

In wearable antennas the radiating patch and the ground plane are made up of copper sheet and the substrate alone is made up of textile materials. As the wearable antennas operate near the human body, it is important to measure the radiation absorbed by the human body. The EM radiation absorbed by human body is measured in terms of Specific absorption rate (SAR) [7]. Specific absorption rate (SAR) is a measure of the rate at which energy is absorbed by the human body when exposed to radio frequency (RF) [8]. In this paper a textile antenna with hexagonal slot is proposed for wearable applications and its performance is analyzed.

II. ANTENNA DESIGN

The proposed antenna has a square patch with a size of 25x25 mm^2 and is fed by 50Ω transmission line using the microstrip feed line[9]. The antenna comprises a ground plane of length L and width W with the hexagonal slot cut from the ground plane as shown in Fig.1. The hexagonal slot has a side length of S1 and the distance from its center to the vertex of the slot is P1. There is an electromagnetically coupled hexagonal parasitic patch of side length S2 with distance from its center to the vertex being P2 printed on the same substrate. Table.1 shows the dimensions of the proposed antenna.



(a) (b)

Figure 1: Hexagonal Slot Antenna Configuration (a) Front view (b) Back view

Table 1: Antenna Dimensions

Dimensions	Values (mm)
L	25
W	25
P1	10.7
P2	4
S1	10.5
S2	5
W_f	1.6
L_f	9.75
L_{off}	2.75

Textile materials like Polyester, Jean and Cotton are used as substrates. The properties of substrates such as dielectric constant, thickness and loss tangent are tabulated in Table 2.

Table 2: Substrates Properties

Substrate	Dielectric Constant(ε_r)	Height(mm)	Tangent Loss(tanδ)
Polyester	3.2	1.2	0.003
Jeans	1.7	3.5	0.025
Cotton	1.51	3.2	0.020

The parasitic patch is positioned at the point of origin, which is surrounded by a wide hexagonal shaped slot. The area of this slot is controlled by either variation in P1 or P2. The hexagonal slot antenna is excited by a microstrip feed line placed beneath the substrate, l_f in length and W_f in width. The gap between the center of the parasitic hexagonal patch and upper end of the projected microstrip feed line is termed as L_{off}. The microstrip feed line excites the parasitic patch electromagnetically through the hexagonal shaped slot. The impedance matching condition for the maximum transmission of signals from the feed line to the parasitic patch is attained by optimization of the parameters P2, feed length l_f and gap L_{off}.

Textile antennas are more preferred for wearable applications due to their effective cost, low weight and low profile. The bandwidth of textile antennas can be increased by increasing the substrate thickness, by using a low dielectric substrate and various feeding techniques. Lower the dielectric constant, lesser will be the surface wave losses.

III. RESULTS AND ANALYSIS

A. Simulation Results

The proposed hexagonal slot antenna is designed and analyzed by FEM based HFSS 13.0 (High frequency structural simulator) software. For SAR calculation, CST (Computer Simulation Technology) tool is used. The performance of the proposed hexagonal slot antenna is analyzed in terms of Return loss (S_{11}), VSWR, Gain, Radiation Pattern and SAR values. The simulated Return loss S_{11} plot over frequency with textile substrates is shown in Fig.2. The Polyester substrate covers a bandwidth of about 2GHz (4.2GHz-6.2GHz) and it provides a return loss of about -18 dB at a frequency of 5GHz. The Jean substrate covers the bandwidth of 1.6GHz (4.2GHz-5.8GHz) and this substrate gives a return loss of about -20 dB at a frequency of 5GHz. The Cotton substrate covers the bandwidth of about 1.6GHz (4.6GHz-6.2GHz) and provides a return loss of -18 dB at 5GHz. When compared to other substrates, jean substrate gives a perfect notch at 5GHz. The return loss and the bandwidth of these substrates are achieved based on the dielectric constant and the thickness of the substrates.

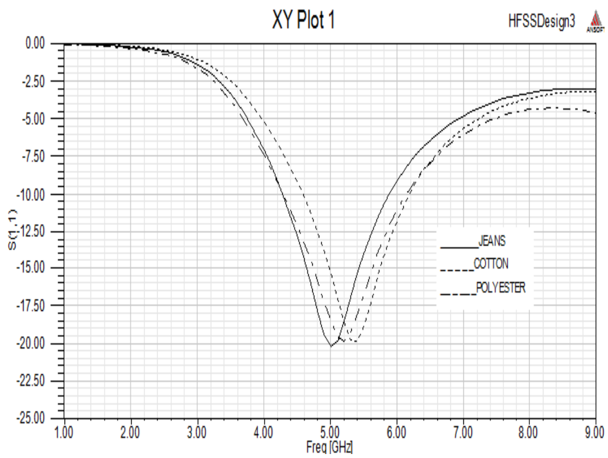


Figure 2: Simulated Return Loss of Textile Antennas

The simulated Voltage Standing Wave Ratio (VSWR) over frequency plot of the proposed antenna with textile substrates is shown in Fig.3. For practical applications the 2:1 VSWR impedance bandwidth is mostly preferred. The VSWR of the hexagonal slot antenna is less than 1.5 for textile substrates which indicates a good impedance matching between the antenna and transmission line with all over its occupied bandwidth.

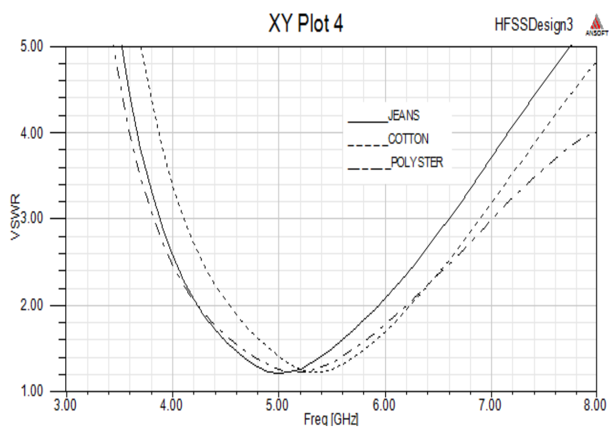


Figure 3: Simulated VSWR of Textile Antennas

Fig.4 shows the simulated gain plot of textile antennas. For slot and dipole antenna the gain should be greater than 2dBi [9]. The designed antenna gain is about 2dBi for textile substrates at resonant frequency. When compared to the other substrates, Cotton has a maximum gain of 2.1dBi at 5GHz because it has less return loss at resonant frequency.

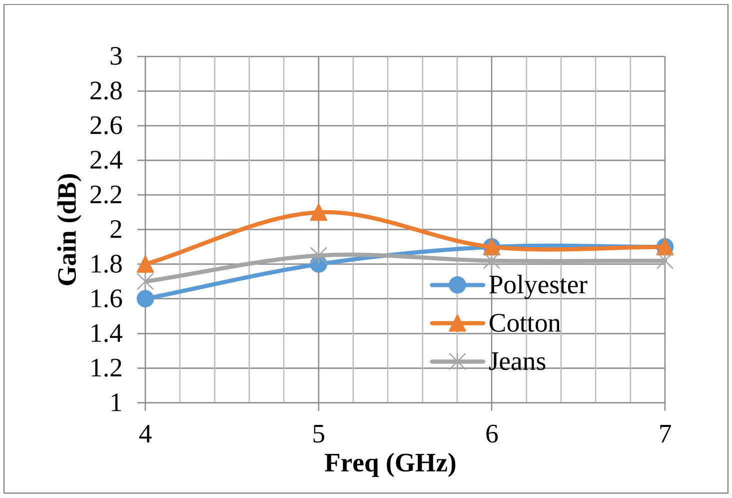


Figure 4: Gain Plot of Textile Antennas

The radiation patterns of the designed antenna are illustrated in Fig.5. Here, the radiation pattern is observed at 5 GHz frequency 5GHz, with phi (φ) has been set to 0 and 90 degree for all values of theta (θ). It can be observed that antenna has omnidirectional pattern in H- plane and bi-directional pattern in E- plane.

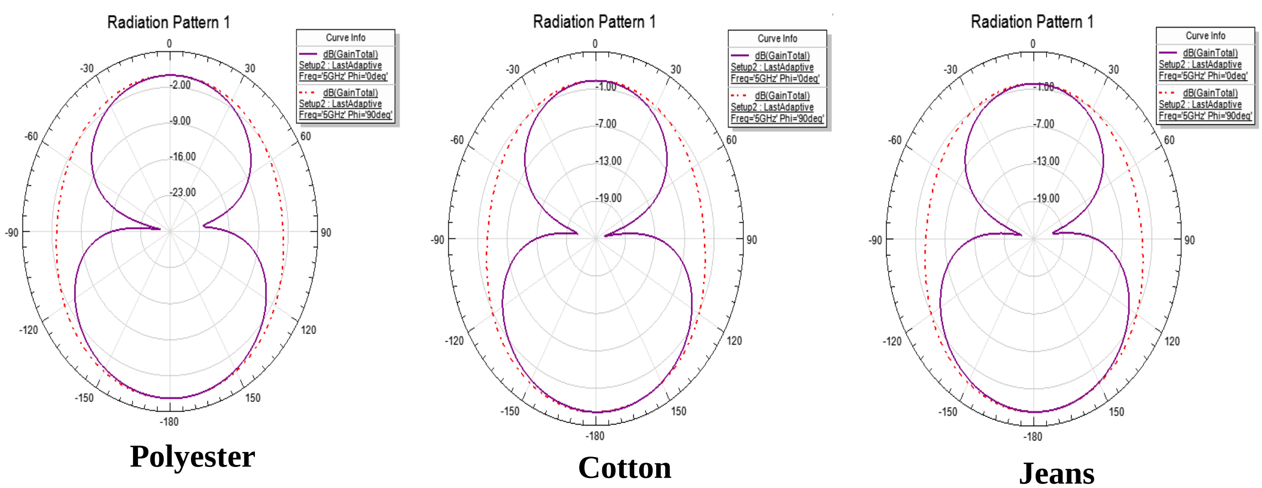


Figure.5: Elevation Radiation Patterns (Theta/deg vs. dBi (phi=0˚ & 90˚) at 5GHz

B. Measured Results

In this section the experimental measurements are obtained by using Agilent Technologies Microwave Vector Network Analyzer. Cotton material is being used as substrate in the fabrication process of designed antenna.Fig.6 shows the front and back side of the fabricated textile antenna. The radiating patches are made with copper strip and are glued with cotton material. Daily wear and tear cotton material is considered for fabrication.

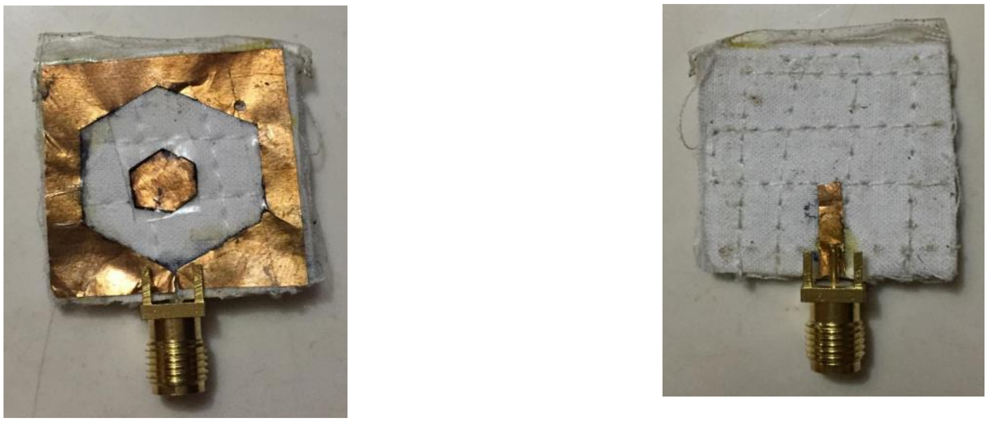
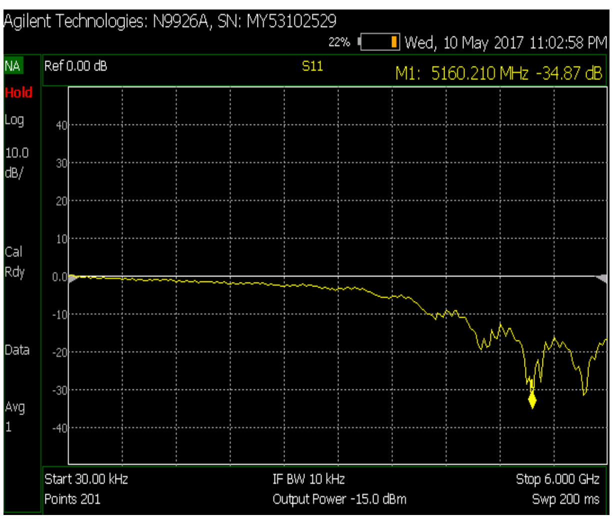


Figure 6: Front and back Side of Prototype Textile antenna with Cotton Substrate)

Fig.7 shows the experimental return loss plot of antenna with cotton substrate. Cotton substrate covers the bandwidth of about 2.6 GHZ (3.9 GHz- 6.5 GHz) and it provides a return loss of about -32 dB at a frequency of 5 GHz. The impedance matching is perfect in this fabricated antenna because the return loss at 5GHz is very less when compared to the simulated results. Fig.8.shows the experimental VSWR plot of fabricated antenna. At 5GHz, the VSWR value is 1.037.



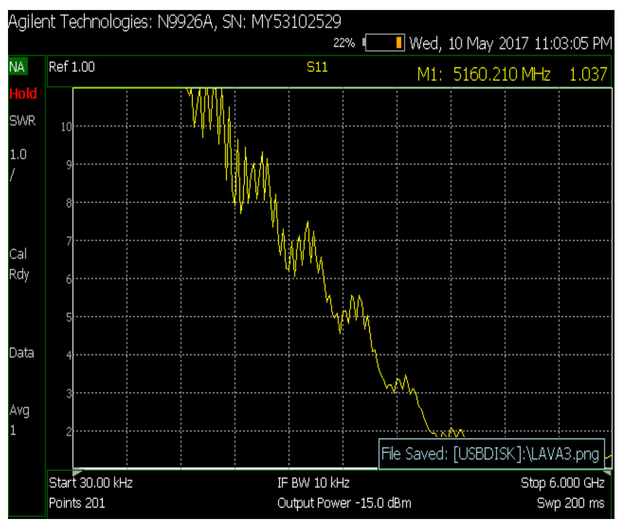


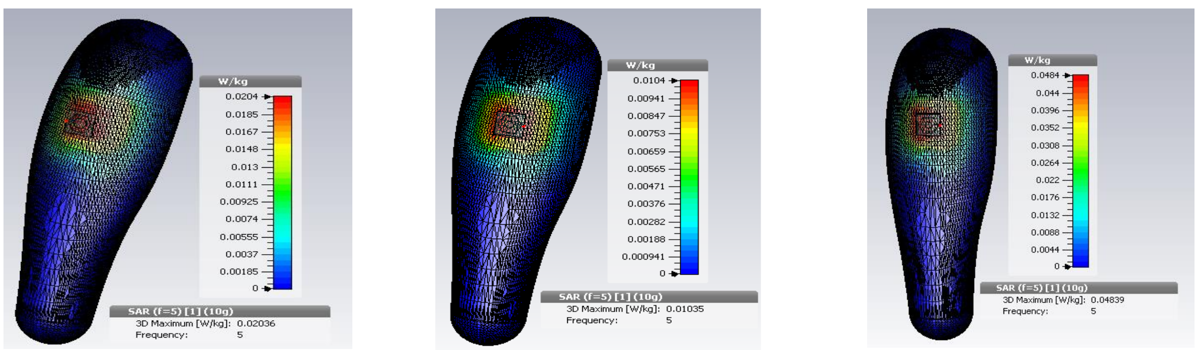
Figure 7: Return loss of the Fabricated Antenna **Figure 8:** VSWR of the Fabricated Antenna

C.SAR Measurement

For the measurement of Specific Absorption rate, CST Microwave Studio is used. Specific absorption rate (SAR) is a measure of the rate at which energy is absorbed by the human body when exposed to radio frequency. It is defined as the power absorbed per mass of tissue and has units of watts per kilogram (W/kg) [10]. SAR for electromagnetic energy can be calculated from the electric field within the tissue as:

$$\text{SAR}=\frac{1}{V}\int\frac{\sigma(r)|E(r)|\hat{}2}{\rho(r)}dr \qquad \text{-------- (1)}$$

σ is the sample electrical conductivity, E is the RMS electric field, ρ is the sample density, V is the volume of the sample. In this paper, a numerical Specific Anthropomorphic Mannequin (SAM) hand phantom [11] with Relative permittivity (εr) of 32.6 and Conductivity (σ)S/m of 1.26 is used. The peak SAR values (spatial-peak SAR [IEEE-1529]) are averaged over 1 and 10 g of human tissues by setting excitation equal to 0.6 Watts. SAR is usually averaged either over the whole body, or over a small sample volume (SAR value of 2 W/kg (SAR) absorbed per 10 g and 1.6 W/kg per 1 g of body tissue) [12]. Based on the dielectric properties, each substrate will have different absorption and depositing the radiation from the mobile phone to the human body.



(a) **(b)** **(c)**

Figure 9: Radiation Effects of Textile Antennas with (a) Polyester (b) Jeans (c) Cotton Substrates

The hand phantom model is made of skin and the blood flow. Fig. 9 shows the radiation effects on hand model with textile substrates. SAR effect onto the user's hand is observed at a distance of 1cm and 1.5cm from the hand model for textile substrates (Polyester, Jeans & Cotton). Table 3 shows the average SAR values of the proposed antenna. From the above SAR analysis, while increasing the distance from the antenna to the human hand the radiation absorbed by the human body is decreased

Table 3: SAR Values of Textile Substrates

Substrate	SAR(W/kg)-10g of body tissue	
	1cm from hand	1.5cm from hand
Polyester	0.0204	0.0185
Jeans	0.0484	0.0450
Cotton	0.0104	0.0100

IV. CONCLUSION

This proposed work presents a compact hexagonal slot antenna for wearable applications. This slot antenna is designed using textile substrates like Polyester, Jean and Cotton. The proposed antenna with textile substrates structure resonates at 5GHz. Over the resonating frequency, the maximum antenna gain is 2dBi. Hence it is concluded that the proposed antenna is suitable for wireless device applications. The proposed slot antenna is validated using both simulated and experimental results; the experimental results are better compared to the simulation results. This proposed work also analyzed the effects of EM radiation on the human hand. The specific absorption rate (SAR) is measured at different distances from the antenna to the human hand. The average SAR values for Polyester, Jeans and Cotton are 0.02036 W/kg, 0.04839 W/kg and 0.01035 W/kg. Because of the low SAR values the proposed antenna can be used for biomedical applications.

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