Design and simulation study of antenna for wireless body area network (WBAN)

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Abstract
In this work, a flexible microstrip patch antenna has been designed to be operated at frequency 2.45GHz (ISM band). Three different materials have been used in this work which is rubber with permittivity of 3.0, loss tangent of 0.02 and thickness of 2.70mm, polydimethylsiloxane (PDMS) with dielectric constant of 2.71, loss tangent of 0.0134 and thickness of 1mm, and jeans with permittivity of 1.7, loss tangent is 0.025 and thickness of 1mm. Different substrate permittivity affect the antenna performance in various ways. The antenna is designed using CST Studio Suite 2019 software and the parameter such as return loss, VSWR, gain, directivity, and radiation pattern are analyzed. Here, the antenna performance when bending at five different angle, SAR value using human body layer and antenna performance when attach to the human arm model will be discuss in this paper.

Keywords: Microstrip patch antenna, ISM band, WBAN, PDMS, wearable antenna, SAR, CST SS

1. Introduction
The rapid advancement of technology has led to an increase in the medical sector and the introduction of a new technology, namely the Wireless Body Network (WBAN). A wireless body network (WBAN) is a network of sensors installed on the human body. The term "WBAN" was introduced by Van Dam in 2001. For the design, a micro-band patch antenna is used because it is the best candidate for application to the body. This type of antenna has a radiation beam that is perpendicular to the ground plane (ground), making it able to protect body tissues from radiation [1]. This article describes antenna design and simulation for wireless body area networks (WBAN). This antenna is designed to operate at 2.45GHz (ISM band). Design and analysis were done using CST Studio Suite 2019.

When study about wearable antenna, it is for sure to be used near the body surface. Human body surface not always flat and the radiation will be change when the antenna in the bending states, so it is important to consider the bending effect when the antenna need to be attached to the body surface [1]. In this case, the antenna performance will be tested in five difference bending radius. Because the antenna is so close to the human body, it has certain impacts on it as well. The radiation of antenna can harm the human body so its important to calculated the SAR value. Human body can disturb the communication link between antenna and outside world and also lossy [3]. The impact of antenna performance when attach to human body arm was analyse in this paper. All-important parameters for antenna design such as bandwidth, gain, VSWR, S-Parameter, return loss, directivity, and SAR value can be shown in this project.

2. Substrate materials selection
Polymer based antenna become a popular topic in the field of wearable antenna. It's because of the advantage of antenna substrate that they are low cost and able to withstand mechanical strains. The flexibility of an antenna is depending on the type of material for substrate used. The flexible antenna is sturdy, light and can be withstand mechanical stretching to a certain extent [4]. The qualities of the materials utilised can have an impact on the antenna's performance. The permittivity and thickness of the substrate, for example, determine the bandwidth and efficiency of a planar microstrip antenna [5]. The proposed antenna [1], [6], [7] used denim material to increase comfortable level and easy to integrated into clothes. The substrate material used in [3] is bed sheet cotton with a relative permittivity of 3.27 and the loss tangent is 0.00786. The substrate also has an impact on antenna performance. Textile material has a low dielectric constant, which improves the antenna's impedance bandwidth and lowers surface wave losses [7]. Many materials have been used as a substrate for WBAN antenna. For example, plastic, rubber, textile, paper, PDMS and various natural materials [8].

A microstrip patch antenna is designed for all antenna type to be operated at frequency 2.45GHz in ISM band for short range communication. Three different materials have been used in this work which is rubber with substrate permittivity of 3.0, loss tangent of 0.02 and thickness of 2.70mm[9], polydimethylsiloxane (PDMS) with substrate permittivity of 2.71, loss tangent of 0.0134 and thickness of 1mm[10], and jeans with permittivity of 1.7, loss tangent is 0.025 and thickness of 1mm[11]. The material used for all antenna design is copper for patch and ground plane.

3. Antenna design and implementation
In this work, a microstrip patch antenna has been design using CST SS software. The initial design and parameter are based on design in[9]. However, this article proposed the antenna that operated at 2.4GHz so some modification need to do to make sure the antenna is operated at 2.45GHz. To get a frequency that operates at 2.45GHz, the approximated dimension of the antenna width and patch is calculated using the microstrip patch formula. Then the original design needs to be scaled and further modified to obtain the frequency at 2.45GHz. The proposed design for this work is as shown in figure 1 for rubber substrate, figure 2 for PDMS substrate and figure 3 for jeans substrate.

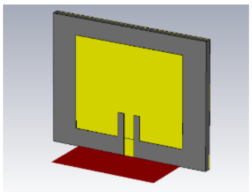

Fig. 1. Antenna using rubber substrate

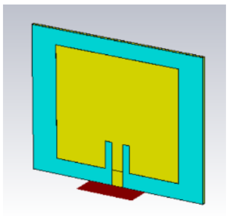

Fig. 2. Antenna using PDMS substrate

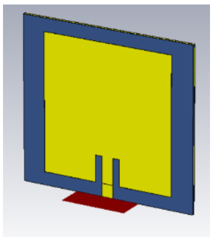

Fig. 3. Antenna using jeans substrate

Table I below shows the size comparison parameter for all antenna after frequency 2.45GHz is achieved. Rubber shows the lowest patch size with dimension of 42x34.10mm, follow by PDMS with dimension of 43x36.83mm and the biggest one is jeans with dimension of 46.13x3.82mm. The dimension for ground and substrate for all antenna is constant. We can conclude that, the size of antenna reduced when the dielectric permittivity is high.

TABLE I. : Antenna parameter

Parameter	Rubber	PDMS	Jeans
Operating Frequency (GHz)	2.4531	2.4529	2.45
Dielectric Permittivity	3	2.71	1.7
Rectangular Patch Width (mm)	42	43	45
Rectangular Patch Length (mm)	34.10	36.83	46.13
Feeding Width (mm)	3.82	3.82	3.82
Feeding Length (mm)	6.45	5.09	4.37
Dielectric and Ground Plane Width (mm)	60	60	60
Dielectric and Ground Plane Length (mm)	47	47	55
Dielectric Thickness (mm)	2.70	1	1
Ground Thickness (mm)	0.064	0.064	0.064

4. Bending of microstrip patch antenna

When we speak about WBAN antenna, it's important to test the antenna under bending conditions because the antenna needs to be attached to the body and the human body is not always flat [3]. Because of the irregular shape of the human body and the fact that there are different human sizes on this planet, the antenna must be tested at a variety of bending radii. In this part, the performance of the antenna is testing under bending condition. The bending condition is analysis using 5 radius of conformal which is 20mm, 30mm, 45mm, 60mm and 70mm [12]. The parameter such resonance frequency, reflection coefficient and VSWR value will be discuss in this part.

Figure 4 shows the s-parameter for rubber substrate antenna. When bending the antenna at radius 20mm, the resonance frequency is 2.449GHz with return loss -20dB. The value for antenna drop to 2.441GHz with return loss -20.568dB for radius 30mm, 2.435GHz with return loss -21.105dB for radius 45mm and 2.434GHz with return loss -18.706dB when bending at radius 60mm. The resonance frequency value increase to 2.437 with resonance frequency -19.408dB when the antenna is bend at radius 70mm. All resonance frequency and return loss for this antenna is acceptable because it's in the range of ISM band which is 2.4GHz until 2.5GHz even the antenna is bending in certain condition. The VSWR for all bending condition in this part show the highest value is below than 1.3 which is acceptable for an antenna.

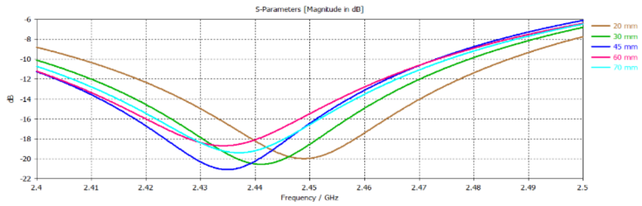

Fig. 4. S-parameter for rubber antenna

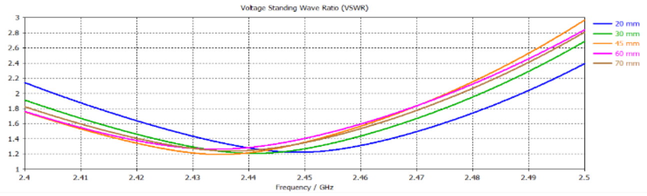

Fig. 5. Rubber VSWR value in bending condition

For PDMS antenna in figure 6, the resonance frequency when bending the antenna in radius 20mm, 30mm, 45mm, 60mm and 70mm is 2.423GHz, 2.412GHz, 2.403GHz, 2.401GHz and 2.403GH. The return loss value is -16.903dB, -20.714dB, -28.733dB, -25.814dB and -27.356dB. The antenna range for all bending condition for this antenna is between 2.4GHz until 2.43GHz, which mean it's still in the ISM band range. In figure 7, the PDMS VSWR value in bending condition shows the highest value is 1.613 when bending at 20mm and the lowest is 1.076 when bending at 45mm.

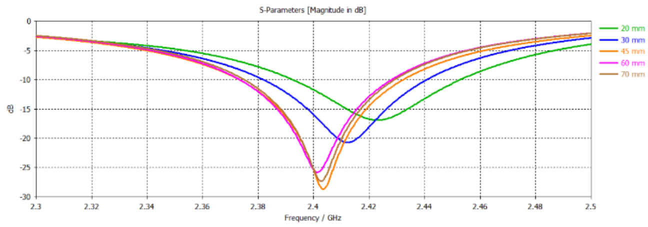

Fig. 6. S-parameter for PDMS antenna

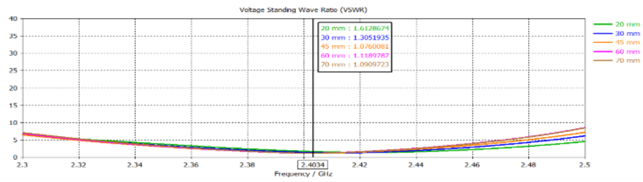

Fig. 7. PDMS VSWR value in bending condition

Figure 8 shows the S-parameter for the Jeans substrate antenna. The resonance frequency for all bending conditions in this antenna is between 2.4GHz and 2.41GHz, which is in the range of the ISM band. The return loss value under -10dB for all conditions is acceptable, which means the performance for this antenna is acceptable when the antenna is bent. VSWR value in figure 9 shows the good value for all bending condition because the value is below than 2. To conclude, the frequency for all antennas will shift to the left when the antenna is bent.

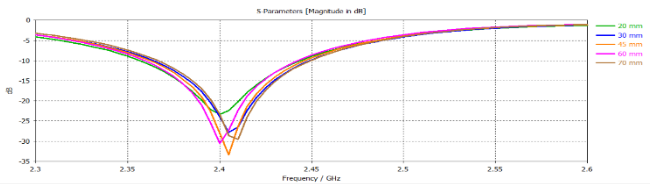

Fig. 8. S-parameter for jeans antenna

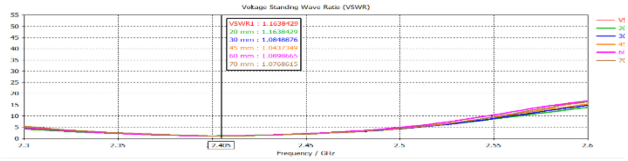

Fig. 9. Jeans VSWR value in bending condition

5. SAR on human body layer

Another condition that needs to be analysed for WBAN antenna is the effect of the human body on antenna performance. This antenna is placed on the human body. The radiation from this antenna can harm the human body, so it is important to calculate the SAR value. For this project, the human body layer was chosen to calculate the SAR value. To speed up the computation, the tissue model was simplified to four layers for simulation [13]. This human body layer as shown in figure 10, consists of four layers, which are skin, fat, muscle, and bone. The total dimension of this model is 85x65x4mm2. The properties of this human tissue layer are based on the material library in the Ansys HFSS simulator [14]. The properties are as shown in table II .

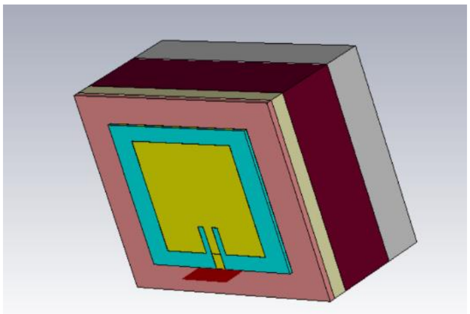
Fig. 10. Human body layer model

TABLE II. Properties for tissue model

Properties (material) for the tissue-model.

Materials	Skin	Fat	Muscle	Bone
ε_r	37.95	5.27	52.67	18.49
$\sigma(S/m)$	1.49	0.11	1.77	0.82
Density (kg/m3)	1001	900	1006	1008
Thickness (mm)	2	5	20	13

To investigate the radiation effect of the design antenna on human body, the value is record in three frequency which is at 2.4GHz, 2.45GHz and also 2.5GHz. Table III shows the SAR value for rubber antenna is 1.13W/kg, 1.42W/kg and 1.31W/kg for 1g tissue. For 10 g tissues, the SAR value is 0.577W/kg, 0.69W/kg, and 0.598W/kg for frequency 2.4GHz, 2.45GHz and 2.5GHz.

TABLE III. SAR value for rubber antenna

Rubber	SAR (W/kg) at frequency 2.4, 2.45 and 2.5 (GHz)		
	2.4	2.45	2.5
For 1g of tissue	1.13	1.42	1.31
For 10g of tissue	0.577	0.69	0.598

Table IV shows the SAR value for antenna that used PDMS substrate. The peak SAR value for this antenna at 2.4GHZ, 2.45GHz, and 2.5GHz is 0.955W/kg, 1.54W/kg and 1.27W/kg for 1g tissue and 0.408W/kg, 0.642W/kg and 0.512W/kg for 10 g tissue. These SAR values are very low compare to maximum SAR limit of 2W/kg in the European standard for 10 g tissue

TABLE IV. SAR value for PDMS antenna

PDMS	SAR (W/kg) at frequency 2.4, 2.45, 2.5 (GHz)		
	2.4	2.45	2.5
For 1g of tissue	0.955	1.54	1.27
For 10g of tissue	0.408	0.642	0.517

Table V shows the SAR value for jeans substrate. At frequency 2.4GHz, SAR value is 0.798W/kg for 1g tissues and 0.345W/kg for 10g of tissue. For 2.45GHz, SAR value is 1.08W/kg for 1g tissues and 0.449W/kg for 10g tissues. For 2.5GHz, SAR value is 1.03W/kg for 1g tissue and 0.417W/kg for 10 g tissue. The SAR value for jeans substrate shows the lower value compare to rubber and PDMS. All SAR value for these 3 substrates is very low compared to the maximum SAR limit of 2W/kg in European standard for 10g tissue and 1.6W/kg in US standard for 1 g of tissue. It can be concluded that all SAR value in this design is following the requirement.

TABLE V. SAR value for jeans antenna

Jeans	SAR (W/kg) at frequency 2.4, 2.45 and 2.5 (GHz)		
	2.4	2.45	2.5
For 1g of tissue	0.798	1.08	1.03
For 10g of tissue	0.345	0.449	0.417

6. Performance analysis using human arm model

This section is to analyse the performance of the antenna using the human arm model. Because the antenna is so close to the human body, it has certain impacts on it as well. The human body can disturb the communication link between the antenna and the outside world and also cause lossy [3]. The material properties for this human body arm are based on table II, so a four-layer cylinder with a radius of 40 mm is simulated to imitate the arm of the human body. To test the performance, the antenna cannot be attached directly to the body. The antenna is placed 5 mm from the human arm model to increase the antenna performance and avoid close contact and also to decrease the antenna radiation and SAR value[14]. To fill the gap, the Styrofoam with thickness of 5mm is used because of its permittivity value is closed to the air which is εr =1.1 [13]. The parameters that will be analysed are resonance frequency, reflection coefficient, VSWR, gain, directivity and SAR value. The simulated design for the human arm model is as shown in figures 11 below.

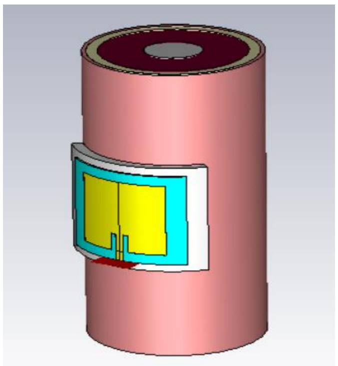
Fig. 11. Human body arm model

Figure 12 shows the S-parameter for three types of substrates, which are rubber, PDMS, and jeans. The resonance frequency for rubber is 2.419 GHz, which is in the range of the ISM band. However, the frequency for PDMS and jeans decreased to 2.357 GHz and 2.387 GHz when we attached the antenna to the human arm model. The reflection coefficient value for jeans shows the lowest value, which is -40.67dB, followed by PDMS, which is -20.33dB, and lastly, rubber, at -16.85dB. The bandwidth for rubber is (2.376-2.464) GHz, for PDMS is between (2.33-2.38) GHz, and for jeans is (2.348-2.43) GHz. Rubber antenna substrate can maintain the frequency in the ISM band when attached to a human arm model.

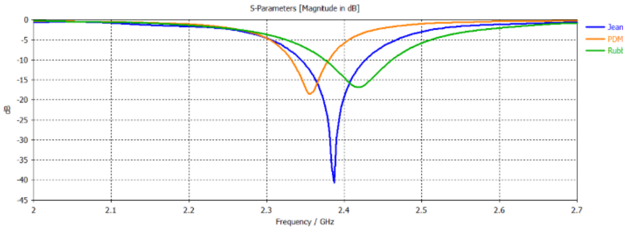

Fig. 12. S-parameter for three substate

Table VI below show the parameter results for resonance frequency, reflection coefficient, gain, directivity and also VSWR value for antenna that used rubber, PDMS and jeans substrate. The value for resonance frequency and reflection coefficient has been discuss before. Rubber substrate antenna shows the higher gain value which is 3.626dBi, followed by jeans 1.926dBi and also PDMS 1.77dBi. The directivity for jeans, 6.282dBi shows the higher value than rubber and PDMS which is 5.769dBi and 6.11dBi. Results for VSWR shows the good value for each antenna because the value is in the range of 1 and 2.

TABLE VI. Results when attaching the antenna to the human arm model

Parameter	R=40mm		
	Rubber	PDMS	Jeans
Resonance Frequency (GHz)	2.419	2.357	2.387
Reflection coefficient (dB)	-16.854	-20.33	-40.668
Voltage standing wave ratio (VSWR)	1.335	1.213	1.019
Gain (dBi)	3.626	1.77	1.926
Directivity (dBi)	5.769	6.11	6.282

Table VII shows the SAR value for rubber, PDMS, and jeans when the antenna is attached to the human arm model. This SAR value for all antennas is very satisfying because it is lower than the maximum limit value. PDMS and jeans show very low SAR values compared to rubber. In conclusion, all these antennas are not dangerous to the human body, even if the antenna is bent by 40mm, but there must be a distance of at least 5mm to maintain the performance of the antenna.

TABLE VII. SAR value for human body arm model

Material	Frequency at 1g and 10 g of tissue					
	2.4GHz		2.45GHz		2.5GHz	
	1g	10g	1g	10g	1g	10g
Rubber	1.277	0.703	1.302	0.715	1.071	0.585
PDMS	0.286	0.219	0.141	0.085	0.124	0.059
Jeans	0.368	0.185	0.266	0.139	0.152	0.084

7. Conclusion

To conclude, before designing a WBAN antenna, need to know the parameters needed, such as the material, type of feeding method, type of antenna, dielectric constant, resonance frequency, and etc. Because this antenna is attached to the body, the effect of antenna radiation on the body and the effect of the antenna in bending conditions are important to consider. The antenna size and material are also important in designing WBAN because they will affect the user's comfortability. As a result, the antenna must be small enough, and the material used must be soft and bendable so that it does not cause discomfort when applied to the body's surface.

Three microstrip patch antennas have been designed with different substrate permittivity, which is 3 for rubber, 2.71 for PDMS and 1.7 for jeans. Rubber is the smallest in size when designed at 2.45GHz, followed by PDMS and jeans. It can be concluded that the size of the antenna will decrease when the dielectric permittivity is increased. For antenna performance when bent to a certain radius, it shows that the resonance frequency will drop, which means the frequency value will shift to the left when the antenna is bent, but the value for all three types of antennas is still acceptable. The SAR value for all designs is also acceptable because all values are below the maximum SAR limit of 2W/kg in the European standard for 10g tissue and 1.6W/kg in the US standard for 1g of tissue. Antenna performance when attached to a human arm model shows the acceptable SAR value for all antennas, but the resonance frequency value for this antenna is decreased. The bandwidth for rubber and jeans shows that this antenna can still be operated in the ISM band, but for the PDMS antenna, it will operate in another band when attached to the human body arm model. Based on this project, the best antenna design to be proposed for WBAN is rubber because of its performance after testing in many situations.

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