Bending Effects Study on Flexible Wearable Antenna for 2.45 GHz Body Centric Wireless Communications

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ARTICLE HISTORY	ABSTRACT
	This study aims to investigate the bending effects on the flexible wearable antenna by using copper nanowires and polydimethylsiloxane (PDMS). This project focuses on the bending effect on the proposed wearable antenna in the presence of skin tissue and at free space. The radiation characteristics were simulated and analyzed when the antenna was under flat and bent conditions. The performance result of return loss and radiation pattern (E-field and H-field) of proposed wearable antenna was analyzed. The material for the proposed antenna is designed to be flexible and wearable for the application of body-centric wireless communication (BCWCs) at the frequency of 2.45 GHz with the approval specifications of industrial, scientific and medical (ISM) band. Radiator for the proposed wearable antenna is fabricated using copper nanowire, and the antenna substrate is by using polydimethylsiloxane (PDMS). The performance result of the proposed wearable antenna was simulated by using CST microwave studio. From the simulated result for different bending angles, a conclusion was drawn that bending of structure can improve the impedance matching and return loss during the bent condition. However, the resonant frequency tends to shift as the antenna is bent up to 50°. At the critical angle of 70°, the frequency is shifted to a lower frequency.

1. INTRODUCTION

In the past decade, there was a phenomenal increment in the growth of communication and wireless industries. The recently stretchable antenna has been widely researched due to its potential capabilities application from a wearable device to foldable electronics, include a flexible display, flexible energy device, smart skin, breast cancer detection and stretchable circuits [1]. Body-centric wireless communication (BCWCs) has received a promising increment of attention due to modern-day application which required to be low in cost, light in term of weight, possibly maintenance-free and straightforward installation. In the realization of this type of wearable antenna, the flexible structure conductivity material in ground plane and patch with flexible dielectric materials in designing the antenna has to be considered [2].

Following the recent trend, the antenna in an electronic system has to be flexible and capable of bending; thus, different solutions are obligatory. In a recent study, polydimethylsiloxane (PDMS) has become one of the impressive flexible materials for substrate based on the attractive mechanical and electrical properties. PDMS is one of a -based silicone elastomer that has shown several significant radiofrequency and mechanical features that shows a low

permittivity and modifiable dielectric properties. The previous research base on PDMS has reported with the permittivity, ε_r is around 2.76 to 3.00 and lossy tangent tan δ of 0.01 to 0.05 over 0.2 to 5.0 GHz operating frequency[3][4]. Moreover, the fluid state in the PDMS also capable of controlling over substrate thickness and the possibility immersing the radiator of the antenna in the substrate [5]. Other than that, PDMS is well known as a biocompatible polymer which can be used for the application of microfluidics, lab-on-a-chip, and a biomedical device such as intraocular pressure sensor used PDMS as the antenna substrate [6].

Metal nanowire (NW) has attracted considerable attention as a new material conductor for the next generation due to their characteristic and properties. The most common metal nanowire that usually used is silver nanowire (AgNW) and copper nanowire (CuNW). In this research, copper nanowire was used as a radiator of the antenna. The AgNWs/PDMS patch has a conductivity of ~8,130 S/cm [7].

This paper focusses on the bending effect on the proposed wearable antenna in the presence of skin tissue and at free space. The antenna that has been proposed is patch microstrip antenna due to its capability of being operated at 2.4 GHz. This antenna utilizes a unique coupling mechanism between the radiating element and the grounding element [8]. The design of patch antenna can be in various shapes and size such as rectangular, circular, elliptical and other shapes. The radiation of a patch antenna can be manipulated by etching the radiating element pattern in metal trace bonded to the insulating substrate properties by E. Rufus *et al.* [9].

2. DESIGN AND SIMULATION

2.1. Antenna Design

In this paper, the proposed microstrip patch antenna is designed to operate at 2.45 GHz ISM band for BCWCs. The patch antenna is performed and optimized in the CST Microwave Studio.

Figure 1 is the front view of the proposed antenna, which is a rectangular patch antenna. The proposed antenna is in five layers as shown in Figure 2. The antenna performance is analyzed in free space with the presence of a layer of skin tissue. Design curvature is generated for the resonant frequency variations and radiation pattern variations by simulating a wearable antenna that is bent on cylindrical surfaces by a different angle. It was done to simulate the wearable antenna to be bend on the arm that has some curves based on the arm diameter.

Figure 2 shows the feed line of the proposed antenna, which represented by stairs at the transmission line. The fringing field is generated at the two slots along the edge of the patch when a signal is transmitted at the microstrip transmission line as resulting radiation of electromagnetic waves. The generated fringing field that is is influenced by the dimension of the patch and substrate height [2]. Figure 3 shows the ground plane dimension of the proposed antenna.

Table 1 shows the dimension of the proposed antenna after the calculation is done based on the design equation as outlined in the design equation section.
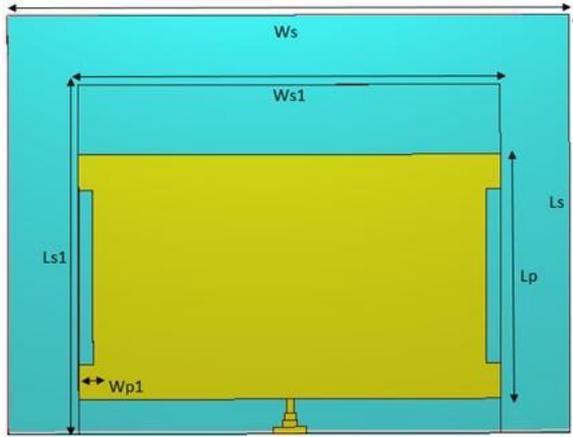
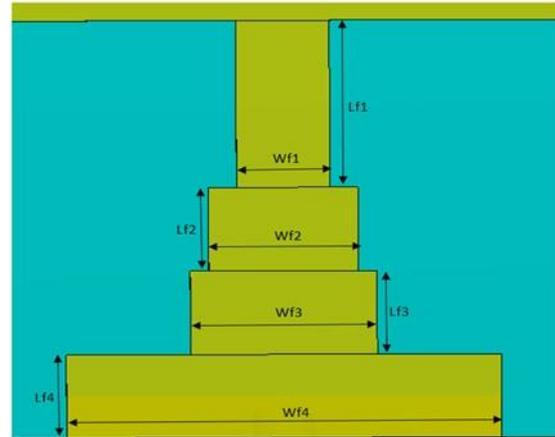Figure 1: Front View of the Proposed Antenna

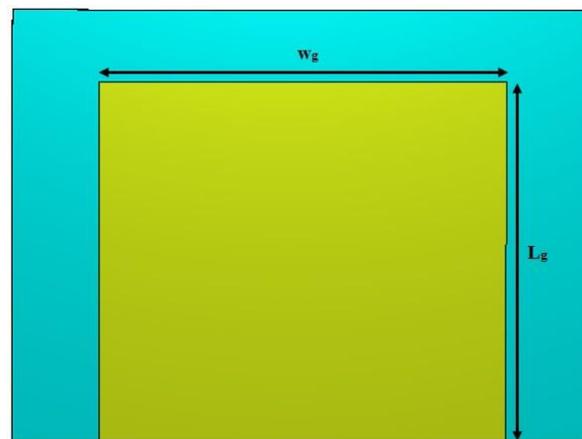Figure 2: Feeder Line of the Proposed Antenna
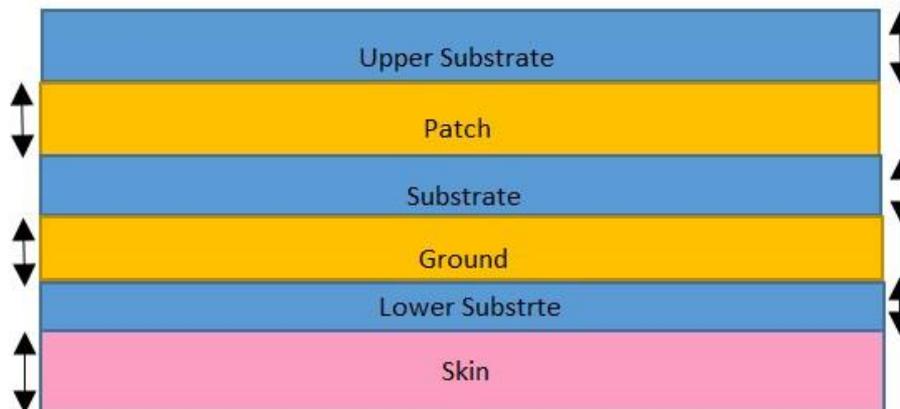

Figure 3: Ground Plane of the Proposed Antenna

Figure 4: Layers of the Proposed Antenna

Table 1: Optimized Antenna Dimensions

Parameters	Optimized Dimension (mm)
Length patch, L_P	35
Width path cut, W_{P1}	2
Length substrate, L_S	59.5
Width substrate, W_S	80
Length substrate cut, L_{S1}	50
Width substrate & Width Path, W_{S1} & W_P	60
Length feeder, L_{f1}	2
Width feeder, W_{f1}	1
Length feeder, L_{f2}	1
Width feeder, W_{f2}	1.6
Length feeder, L_{f3}	1
Width feeder, W_{f3}	2
Length feeder, L_{f4}	1
Width feeder, W_{f4}	4.66
Length ground, L_g	50
Width ground, W_g	56
Upper substrate	0.5
Patch	0.017
Substrate	1.6
Ground	0.017
Lower substrate	0.083
Skin	1.5

2.2. Design Equation

The dimension of the antenna determines the resonant frequency of the patch antenna. To determine the resonant frequency, Equation (1) is computed [10].

$$f_{res} = \frac{c}{2L\sqrt{\varepsilon_{reff}}} \tag{1}$$

Where

c = free-space speed of light

L = length of microstrip patch

ε_{reff} = effective relative permittivity of microstrip patch

To determine the approximate width of the patch antenna can be calculated by using Equation (2) after the resonant frequency is determined.

$$W = \frac{c}{2f_{res}}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{2}$$

Where

W = width of microstrip patch

f_{res} = resonant frequency

ε_r = relative permittivity of mirostrip patch

c = free-space speed of light

To determine the approximate width of the patch antenna can be calculated by using Equation (3) after Equation (4) and (5) are determined.

$$L = \frac{c}{2f_{ress}\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{3}$$

Where

ΔL = extended length of microstrip patch

f_{ress} = resonant frequency

ε_{ress} = effective relative permittivity of mirostrip patch

c = free-space speed of light

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}[1 + 12\frac{h}{W}]^{-1/2} \tag{4}$$

$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \tag{5}$$

2.3. Bending Investigation

To investigate the bending effect of the designed wearable antenna, the antenna is bent at three different angles, at 30°, 50° and 70°. The formula in determining the bending angle of the antenna is determined by using Equation (6). The width of the antenna patch as the radius, the antenna bending angle is depicted in Figure 5 and Figure 6.
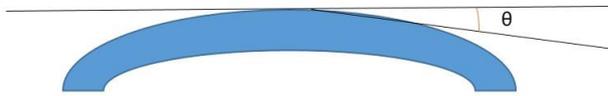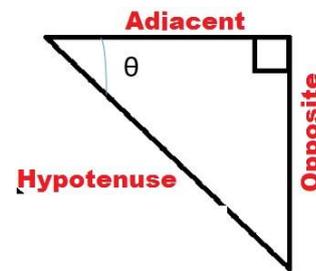

Figure 5: Antenna Bending Angle   Figure 6: Pythagoras Theorem

$$tan\,\theta = \frac{opposite}{adjacent} \tag{6}$$

Where

θ = Measured angle of the central angle in radius

Opposite = Constant value of the length

Adjacent = Radius of the circle

From equation (6) the length of the radius can be calculated; the value of the radius acts as the radius of a cylinder for intended angle in CST environment. The bending antenna was analyzed in two conditions. The first condition of the antenna was analyzed in free space while the other was in the presence of skin tissue.

Figure 7 shows the microstrip patch antenna geometry for different bending angles. This simulation is to imply the simulation the effect of different size of the human arm if the antenna is worn. The difference in antenna bending was simulated to study the performance of the antenna in terms of its return loss, which is discussed further in the next section.
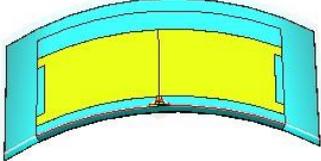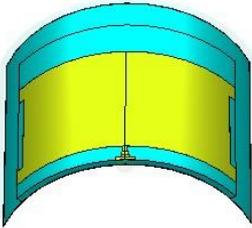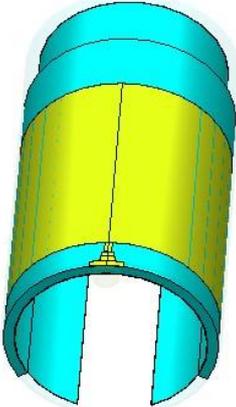
30° bending	50° bending
Patch outer radius = 70.899 mm Substrate outer radius = 70.999 mm	Patch outer radius = 35.1804 mm Substrate outer radius = 35.2804 mm

70° bending
Patch outer radius = 16.1758 mm Substrate outer radius = 16.2758 mm

Figure 7: Microstrip Patch Antenna Bending Geometry for Different Bending Angles

3. RESULT AND DISCUSSION

The bending effect of the designed wearable antenna, which the antenna was bent at three different angles at 30°, 50°, and 70° is discussed in this section. The returning loss performance and the radiation pattern at the bending and flat conditions when the antenna was placed on the skin layer and at the free space are also presented.

3.1. Antenna At Flat Condition

From Figure 8, the return loss in free space is found to be 12.76 dB with the resonance frequency of 2.4 GHz. In the presence of skin, the return loss improved drastically to 33.46 dB, but the resonance frequency is shifted to 2.45 GHz. Figure 9 shows the simulated radiation patterns of the proposed antenna in the flat case. The omnidirectional patterns are observed in the xz plane.
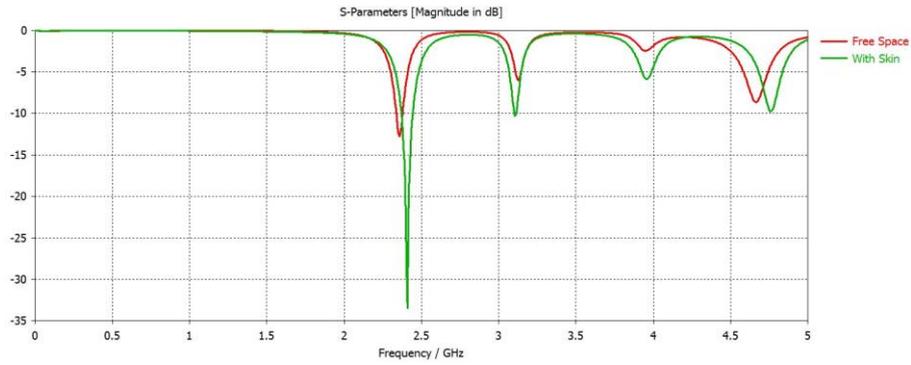
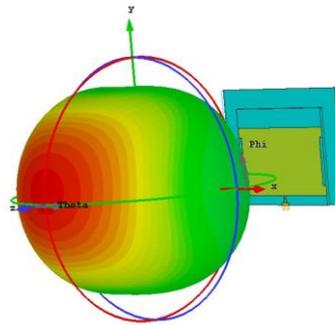Figure 8: Return Loss of the Proposed Antenna under Flat Condition

Figure 9: 3D Radiation Pattern

3.2. Antenna Bending At 30 Degree

From Figure 10, the return loss of the antenna in free space is found to be 18.89 dB with a resonance frequency of 2.45 GHz. In the presence of skin, the return loss drops to 18.04 dB at the same resonant frequency. Figure 11 depicted the omnidirectional radiation pattern of the proposed antenna.
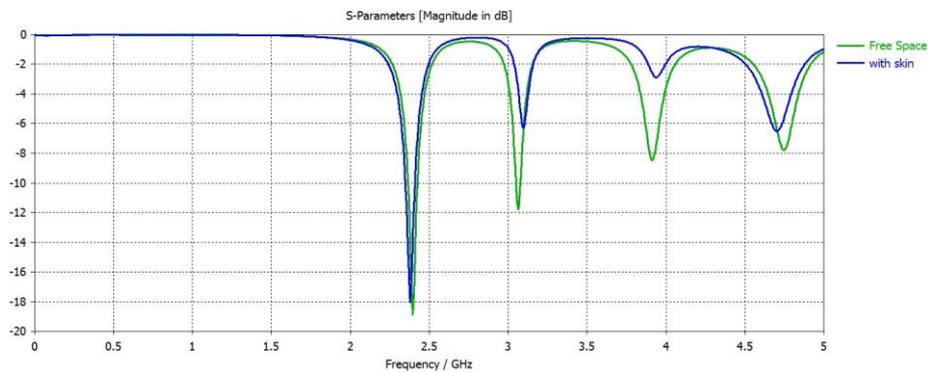

Figure 10: Return Loss of the Proposed Antenna under 30 Degree Bending Condition
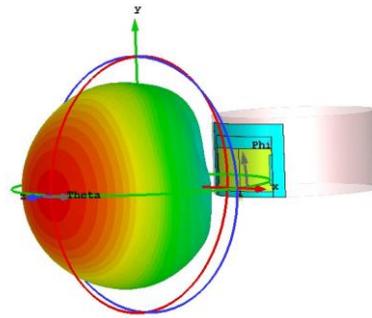
Figure 11: 3D Radiation Pattern

3.3. Antenna Bending At 50 Degree

From Figure 12, S-parameter shows a well impedance matching with result loss of 26.84 dB in free space and 29.36 dB at the presence of skin tissue. Figure 13 shows the radiation pattern of the antenna radiated away from the radiator.
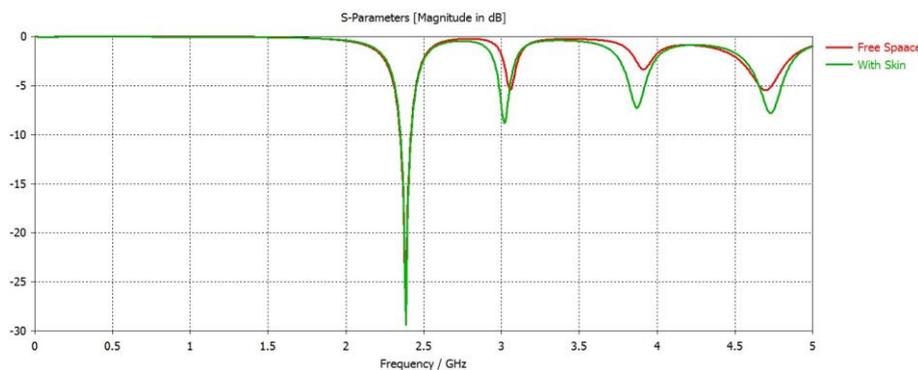

Figure 12: Return Loss of the Proposed Antenna under 50 Degree Bending Condition
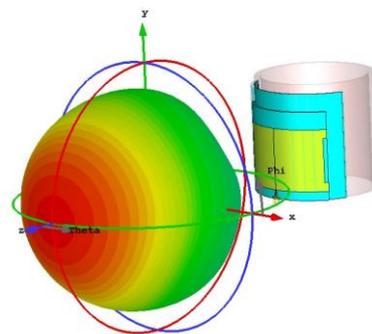

Figure 13: 3D Radiation Pattern

3.4. Antenna Bending At 70 Degree

Figure 14 shows the return loss of the proposed antenna under 70 degree bending condition with and without the skin layer, while figure 15 shows the radiation pattern result for the same bending angle condition.
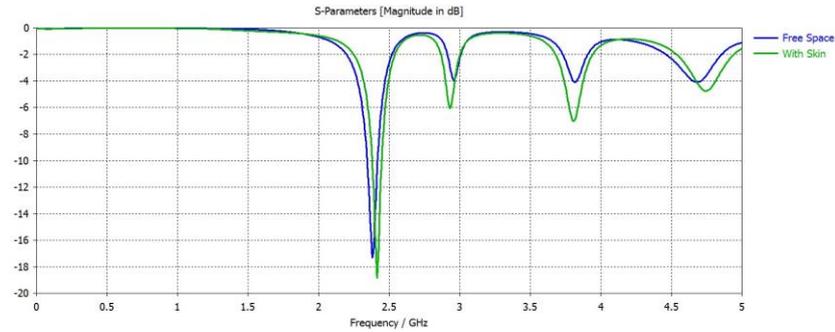

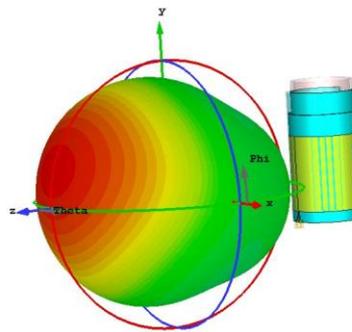Figure 14: Return Loss of the Proposed Antenna under 70 Degree Bending Condition

Figure 15:3D Radiation Pattern

3.5. Comparison Analyses

Figure 16 shows the comparison of S-parameter for all the bending angles and flat conditions with a layer of skin, Figure 17 shows the comparison of S-parameter for all the bending angles at free space when without a layer of skin. The performance of the proposed microstrip antenna was simulated in free space and the presence of skin tissue and is tabulated in Table 2 and Table 3, respectively. By considering 10 dB as an acceptable value of return loss foran excellent wearable antenna design, the return loss performance of the antenna is better with the presence of skin tissue, due to the permittivity of the skin, $\varepsilon_r = 34.5$ and $\tan \theta$ (loss tangent) at 0.347, which can improve the grounding and matching of the antenna and improve the return loss[11]. The return loss in flat condition with the presence of skin is 19.58 dB more than free space condition. The resonance frequency also has shifted in the presence of skin condition due to high permittivity of skin. The simulated result as shown in figure 16, shows that the S_{11} is slightly affected when the antenna is bent to a different bending angle.

With the presence of skin tissues in Table 2, the S_{11} result is at 18.89 dB compared to flat state 33.46 dB. At 50° bending, the return loss is improved to 29.36 dB; where the return loss is at the best performance. However, when the antenna is bent further up to 70°, it is found that the return loss is only 17. 32 dB, not as good as at the 50° bending but still in the range of acceptable return loss for wearable applications. The frequency is shifted to a higher frequency when the bending angle is increased. The radiation pattern in E-field and H-field was observed having an omnidirectional pattern. Most of the power was radiated in the upper hemisphere for each different angles of bending.

From the result, it is shown that antenna return loss and radiation pattern were affected by the various bending angle of the antenna. From the comparison in Table 2 and Table 3 about the S_{11}-parameter simulated result for different bending angles, a conclusion was drawn that bending of structure can improves the impedance matching and return loss during the bent condition. However, the resonant frequency tends to shift as the antenna is bent up to 50°; at the critical angle of 70°, the frequency is shifted to a lower frequency.
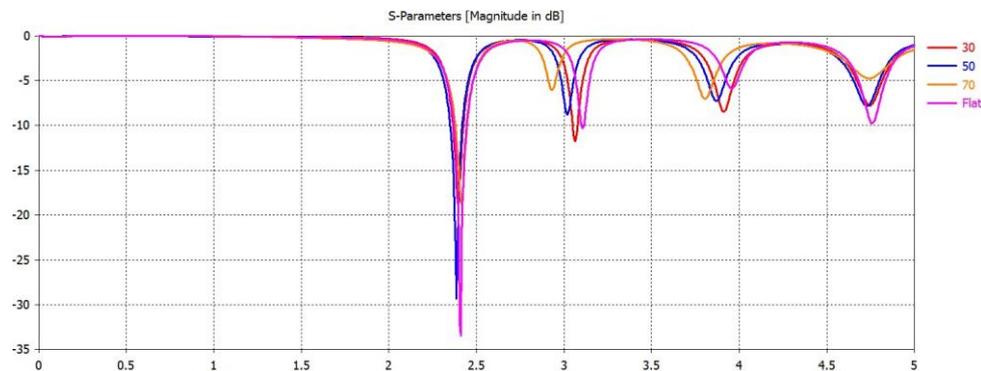

Figure 17: Comparison of S-Parameter for Bending with a Layer of Skin

Table 2: Flat and Bending Antenna Radiation Characteristics with Skin

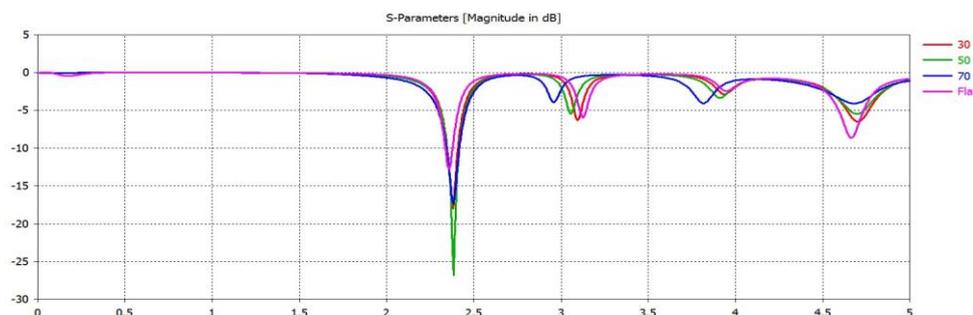| Parameter	Flat	Bending		
	0°	30°	50°	70°
Resonant Frequency (GHz)	2.43	2.45	2.44	2.45
Return Loss, S_{11} (dB)	33.46	18.89	29.36	18.84
Gain (dB)	3.45	5.40	4.63	2.60
Directivity (dBi)	4.788	7.12	6.40	3.78
Bandwidth (-10dB) (MHz)	82.77	67.65	69.09	72.92

Figure 18: Comparison of S-Parameter for Bending in Free Space

Table 3: Flat and Bending Antenna Radiation Characteristics in Free Space without Skin

Parameter	Flat	Bending		
	0°	30°	50°	70°
Resonant Frequency (GHz)	2.36	2.42	2.45	2.41
Return Loss, S_{11} (dB)	12.74	18.04	26.84	17.32
Gain (dB)	6.83	6.36	5.62	2.93
Directivity (dBi)	7.07	6.47	5.71	2.98
Bandwidth (-10dB) (MHz)	44.42	59.76	71.26	75.10

CONCLUSION

The return loss performance analysis of microstrip patch antenna bending at different angles with the presence of skin tissue and in a free space condition without skin tissue has been simulated. H-plane and E-plane bending orientations in the conditions of bending have been investigated too.

In conclusion, the proposed antenna demonstrates good performance for H-plane and E-plane bending orientations in the conditions of bending. The antenna offers excellent mechanical flexibility. Due to the excellent performance when subjected to bending, it can be used in body-centric wireless communications applications.

ACKNOWLEDGMENT

REFERENCES

[1]   S. Lee et al., "Ag nanowire reinforced highly stretchable conductive fibers for wearable electronics," *Adv. Funct. Mater.*, vol. 25, no. 21, pp. 3114–3121, 2015.

[2]   Murad M.A., Bakar A.A., Razali A.R., Hasli M.A.I.M., Khan M.F.A.J., "Bending Effects on Wearable Antenna with Silver Nanowires and Polydimethylsiloxane," *Advanced Computer and Communication Engineering Technology. Lecture Notes in Electrical Engineering*, vol 362. Springer, Cham, 2013.

[3]   G. J. Hayes, J.-H. So, A. Qusba, M. D. Dickey, and G. Lazzi, "Flexible Liquid Metal Alloy (EGaIn) Microstrip Patch Antenna," *TAP_IEEE Trans. Antennas Propag.*, vol. 60, no. 5, pp. 2151–2156, 2012.

[4]   J. Trajkovikj, J. F. Zurcher, and A. K. Skrivervik, "PDMS, a robust casing for flexible W-BAN antennas [EurAAP corner]," *IEEE Antennas Propag. Mag.*, vol. 55, no. 5, pp. 287–297, 2013.

[5]   T. Rai, P. Dantes, B. Bahreyni, and W. S. Kim, "A stretchable RF antenna with silver nanowires," *IEEE Electron Device Lett.*, vol. 34, no. 4, pp. 544–546, 2013.

[6]   Ç. Varel, Y. C. Shih, B. P. Otis, T. S. Shen, and K. F. Böhringer, "Packaging for a wireless intraocular pressure sensor with a solder-filled microchannel antenna," *Proc. IEEE Int. Conf. Micro Electro Mech. Syst.,* no. February, pp. 981–984, 2012.

[7]   N. J. Farcich, J. Salonen, and P. M. Asbeck, "Single-length method used to determine the dielectric constant of polydimethylsiloxane," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 12, pp. 2963–2971, 2008.

[8]   J. Costantine, K. Y. Kabalan, a El-Hajj, and M. Rammal, "New Multi-Band Microstrip Antenna Design for Wireless Communications," *2011 IEEE Jordan Conf. Appl. Electr. Eng. Comput. Technol. AEECT*, vol. 49, no. 6, pp. 1–5, 2007.

[9]   E. Rufus, "Microstrip antenna on kapton substrate for strain sensing applications," *16th Int. Conf. Adv. Commun. Technol.*, pp. 453–455, 2014.

[10]   E. Workman, I. Chang, S. Noghanian, A. S. Patch, and D. Methods, "Flexible Textile Antenna Array," *IEEE International Conference on Electro/Information Technology (EIT),* no. 3, pp. 569–574, 2015.

[11]   V. Karthik, "A Microstrip Antenna at UWB Frequencies for Body Wearable Wireless Devices," *IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS)*, pp. 4–8, 2014.

[12]   S. Ding, J. Jiu, and K. Suganuma, "Stretchable Transparent Conductors Based on Copper Nanowires and Polyurethane," *2015 IEEE 15th International Conference on Nanotechnology (IEEE-NANO)*, pp. 242–245, 2015.

[13]   H. C. Chu et al., "Spray-Deposited Large-Area Copper Nanowire Transparent Conductive Electrodes and Their Uses for Touch Screen Applications," *ACS Appl. Mater. Interfaces*, vol. 8, no. 20, pp. 13009–13017, 2016.

[14]   A. Gentile, F. Ruffino, and M. G. Grimaldi, "Complex-morphology metal-based nanostructures: Fabrication, characterization, and applications," *Nanomaterials,* vol. 6, no. 6, 2016.

[15]   T. Wang, R. Wang, Y. Cheng, and J. Sun, "Quasi in Situ Polymerization to Fabricate Copper Nanowire-Based Stretchable Conductor and Its Applications," *ACS Appl. Mater. Interfaces*, vol. 8, no. 14, pp. 9297–9304, 2016.

[16]   L. Song and Y. Rahmat-Samii, "A Systematic Investigation of Rectangular Patch Antenna Bending Effects for Wearable Applications," in *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 5, pp. 2219-2228, May 2018, doi: 10.1109/TAP.2018.2809469.

[17]   S. N. Mahmood, A. J. Ishak, T. Saeidi, H. Alsariera, S. Alani, A. Ismail, and A. C. Soh, "Recent Advances in Wearable Antenna Technologies: A Review," *Progress In Electromagnetics Research B*, vol. 89, pp. 1-27, 2020.