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Design and biocompatibility analysis of an implantable miniaturized antenna in biosfluids for biomedical and ISM band applications

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Abstract
This work presents the design and Biocompatibility analysis of implantable antenna in bio-fluid environment for Biomedical communication applications. The antennae's topographical structure appears the Yin-Yang symbol and was developed on natural jute felt based material. The developed prototype has a compact dimension of 20×16×1.5 mm^3. The antennas implantability was validated under vigorous testing in bio fluids such as goat blood and plasma and also in the synthetic biofluids such as Simulated body fluid and mediums such as D-MEM. In normal operational conditions the developed antenna functional frequencies are 3.5, 4.9 and 5.8 GHz in the Biomedical and ISM application ranges. While assessing its implantability in bio fluids it was observed that the proposed model functions in above said frequency band applications with some minor variations. Similar observations were also made while testing it under *in-vitro* analysis in synthetic biofluids. The proposed implantable device biocompatibility and lifetime analysis in the biofluids was done in the electrochemical workstation. The observations from the corrosion analysis found that the device has a safe biocompatibility for operating in the implantable conditions.

Keywords: Bio-fluids, biomedical applications, electrochemical work station, implantable antenna, *in-vitro* conditions

1. Introduction

In the recent past, textile antennas have gained popularity and got much attention from developers because it's the critical component in the body-worn communication system. The textile antennas have many more added advantages because of their lightweight, flexibility, ease of integration with the wearer's clothes, and low fabrication cost correlated to a rigid microstrip antenna. For instant, in the field of biomedicine, textile antennas are employed in wearable health care systems such as Vetement de Tele-Assistance Medicale-VTAM (Medical project in which Garments utilized for teleassistance), WEALTHY (a wearable health care system to monitor vitals of the patient in Europe), and the versatile ambulatory system the LIFE SHIRT. Furthermore, all these wearable health screening systems are deployed to transmit vital physiological information to the health practitioner for a diagnosis. In all these systems, textile antennas play a crucial role [1-2].

A circularly polarized textile antenna makes the on-body communication more significant since this feature allows the signal's reception irrespective of the orientation between the transmitter and receiver. It also has an inherent ability to reduce multipath reflections, more resistant to signal degradation due to different weather and better mobility. Thus, the realization of the circularly polarized textile antenna makes the on-body communications more effective because textile materials as substrate are more comfortable to wear in day to day life, more flexible, and lightweight. The literature review shows that in [3], the authors proposed a visually concealed all textile circularly polarized sleeve badge antenna. It was developed on polyester fabric, and conductivity is realized using fiselin material; this model achieves an RHCP radiation pattern. In [4], the authors designed SIW based circularly polarized wearable antenna for the 2.45 GHz ISM frequency band. Expanded rubber was considered substrate, and taffeta fabric was utilized for patch and ground plane conductivity. A slotted split ring textenna is reported in [5]; the square patch's springs are responsible for the dual resonating frequency and the circular polarization feature.

In [4] an implantable dipole antenna was developed on Polydimethylsiloxane (PDMS) substrate with a thickness of 3.2 mm and operating in the bands of ISM. A specific liquid has been used for the *in-vitro* measurements. However, this antenna suffers from its large dimensions of 8.5×25.9 mm^2. The developers of [6] designed a coplanar waveguide fed monopole implantable antenna to monitor the wearer's glucose and blood pressure. It was set to operate in the bands of ISM, and *in-vitro* measurements were measured in a salt and sugars solution in pure water. The authors of [7] designed an implantable printed dipole antenna operating in the bands of 2.4 GHz ISM and MBAN. The antenna was tested on a phantom model, which contains liquids representing the body tissues.

As part of the wearer's outfit (defence personnel or those who undergo medical treatments) or *in-vitro* implantable conditions, the textile antennae are subjected to frequent exposure to body fluids such as the wearer's blood plasma. Those fluids will significantly influence the antenna's performance. A little exposure to blood or plasma significantly changes the antenna's functioning, and complete absorption of blood in implantable conditions worsens the antenna's performance. This study focuses on developing the implantable textile antenna, and its performance is evaluated in implantable conditions (*in-vitro* measurements in body fluids and simulated fluids). Furthermore, the implantability of the antenna in bio-fluid conditions is also evaluated in this study.

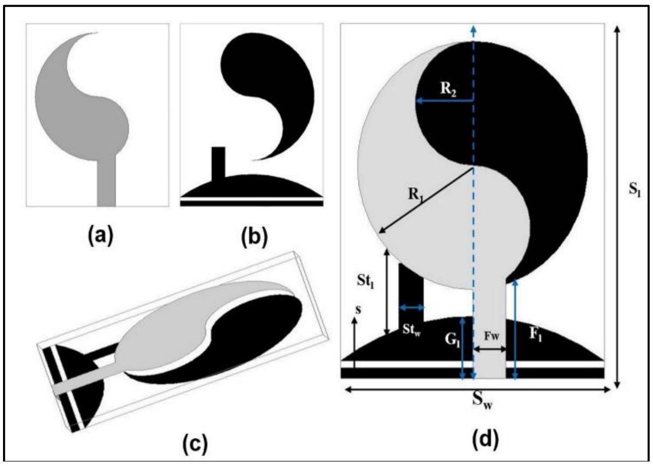


Fig 1: The proposed antennas topology (a) top view, (b) ground view, (c) lateral view, and (d) overall view with geometry.

2 Antenna design method and Topology

The propounded antenna is developed on a jute textile-based substrate [7]. As illustrated in Fig. 1, The antenna's radiating element features a semi-circular geometry, while the ground plane mirrors this shape and is positioned inversely beneath the patch to achieve structural symmetry and optimized radiation performance. The ground plane also contains a stub over an elliptical semi-structure. This stub structure is responsible for the circular polarization in the resonating bands. The radiating element's conductivity is actualized through conductive copper paint. In normal circumstances, the antenna operates in the frequencies of 3.5, 4.9, and 5.8 GHz, as shown in Fig.2. The overall dimensions of the antenna are Sl-20 cm, Sw-16cm, Fl-5.0 cm, Fw-2.0 cm, R1-7.0 cm, R2-3.5 cm, Gl-2.5 cms, S-0.5 cms, Stl-2.5 cms, Stw-1.5 cms.

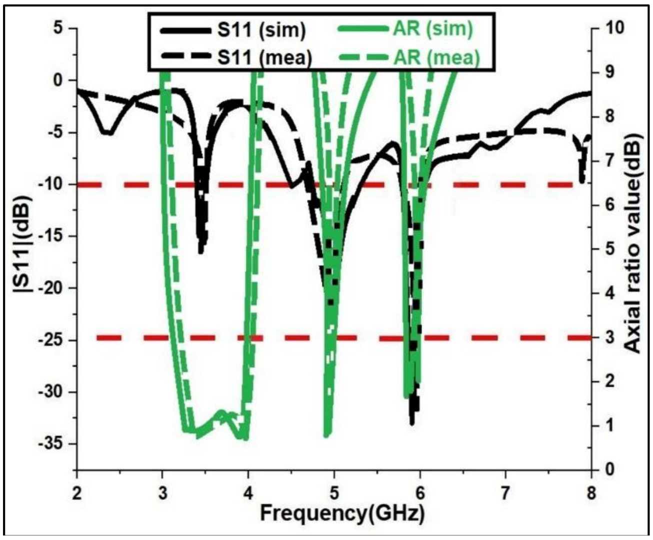


Fig 2: Simulated and measured S11 and axial ratios of the proposed antenna in normal dry condition.

3. Body fluids analysis and Implantability (*In vitro* measurements)

The body consists of 60% of fluids to its total body weight. This watery matrix is called biofluids or body fluids, where cellular metabolic biochemical reactions happen. They are responsible for some vital functions such as the transportation of nutrients and oxygen to all the tissue, temperature regulation, and maintaining the internal environment's constancy. Body fluids are furtherly classified as intracellular fluids and extracellular fluids. Intracellular fluids are liquids found inside the cells, and extracellular fluids are seen surrounding the cells [8-10].

Implantability in Blood

As illustrated in Fig. 3(a), the prototype is wholly inundated in goat blood, which was collected from the slaughterhouse, an anticoagulant (EDTA) was dissolved in it to avoid coagulation of blood [11]. Its kept in the carbon dioxide incubator (at a temperature of 37 degrees centigrade and a 5% carbon dioxide as seen in Fig. 4(a, and b)) to recreate the same possible effects of goat body temperature and blood implantability condition. To mimic the goat body conditions, the antenna was held in the incubator for a period of 8 hours, and also to make sure that the jute material completely absorbs the blood. Then the antenna was tested in the anechoic chamber, and it's operating in the dual bands of WLAN and ISM applications at frequencies ranges from 4.5-5.3 GHz and 5.5-6.1 GHz. As presented Fig. 5(a), the AR, where they are lesser than 3dB limit functioning at 4.6-4.95 GHz and 5.5-6.1 GHz, and it's covering the ISM band. Hence the antenna is operating with circular polarization. As illustrated in Fig. 6(a), the peak gain in the operating frequencies are 8.0, and 8.1 dBi and the efficiency is 80 and 82 percentage.

Plasma *in vitro* Analysis

As illustrated in Fig. 3(b), the propounded model is inundated in goat plasma which was freshly extracted just a few minutes prior to the experimentation [12]. Anticoagulant (EDTA) was used to prevent clotting. It's kept in the carbon dioxide incubator to recreate the same possible effects of goat body temperature and plasma implantability. The antenna was held in the incubator for a period of 8 hours to make sure that the antenna completely absorbs the plasma.

After this process, the antenna was tested in an anechoic chamber, and it's operating in bands of WiMAX, WLAN and ISM applications at 3.3, 4.6-5, and 5.7-5.85 GHz. As shown in Fig 5(b), the AR, where the values are less than 3dB is from 4.8-5 GHz and 5.7-5.85 GHz. As illustrated in Fig 6(a), the gain in the functional frequencies is 8.1, and 8.3 dBi and the efficiency is 83 and 85 percent.

Simulated body fluid *in vitro* Analysis

A SBF is an artificially prepared suspension whose ionic concentration and pH closely replicate those of human extracellular fluid. To explore the antennas functionalities in *in vitro* circumstances and to mimic the body fluids SBF analysis was performed. As presented Fig. 3(c), propounded model was implanted in SBF and kept in the carbon dioxide incubator to recreate the possible effects of goat body implantable conditions. The antenna was held in the incubator for a period of 8 hours to make sure that the antenna completely absorbs the SBF. The antenna was tested in the anechoic chamber, and it's operating in the frequencies of 2.4, 4, 4.7-5.2, and 5.7-6 GHz. As shown in Fig. 5(c) the AR, where the values under the 3dB mark are 4.5-5.2, and 5.75-5.85 GHz, and it's covering the ranges of WLAN and ISM. As illustrated in Fig. 6(b), the peak gain in the operating frequencies is 6.1, and 6.5 dBi and the efficiency is 80 and 81 percent.

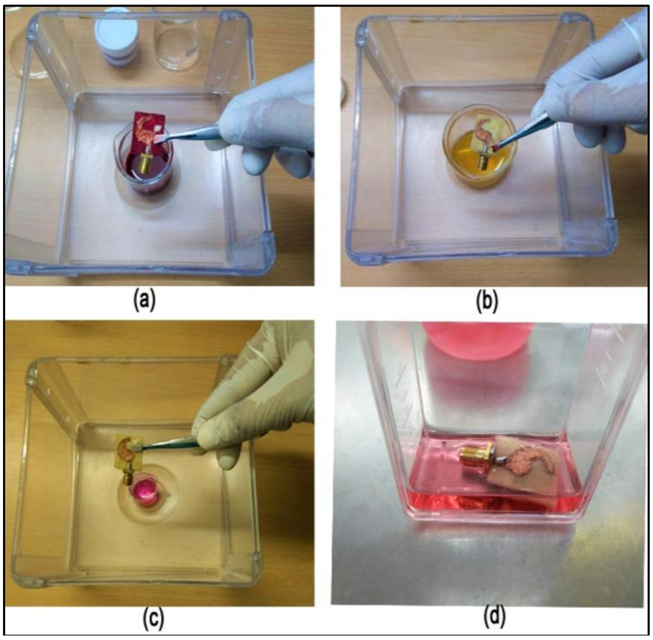


Fig 3: *in vitro* analysis of antenna in (a) blood, (b) plasma, (c) SBF, and (d) DMEM.

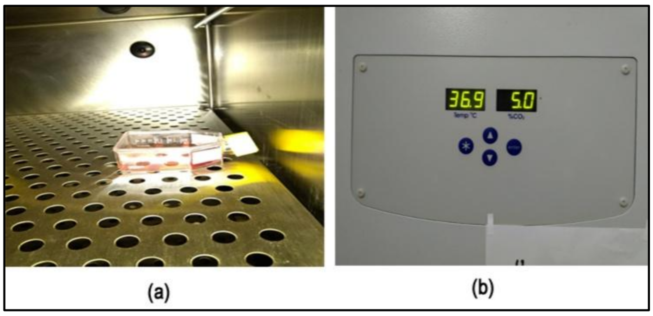
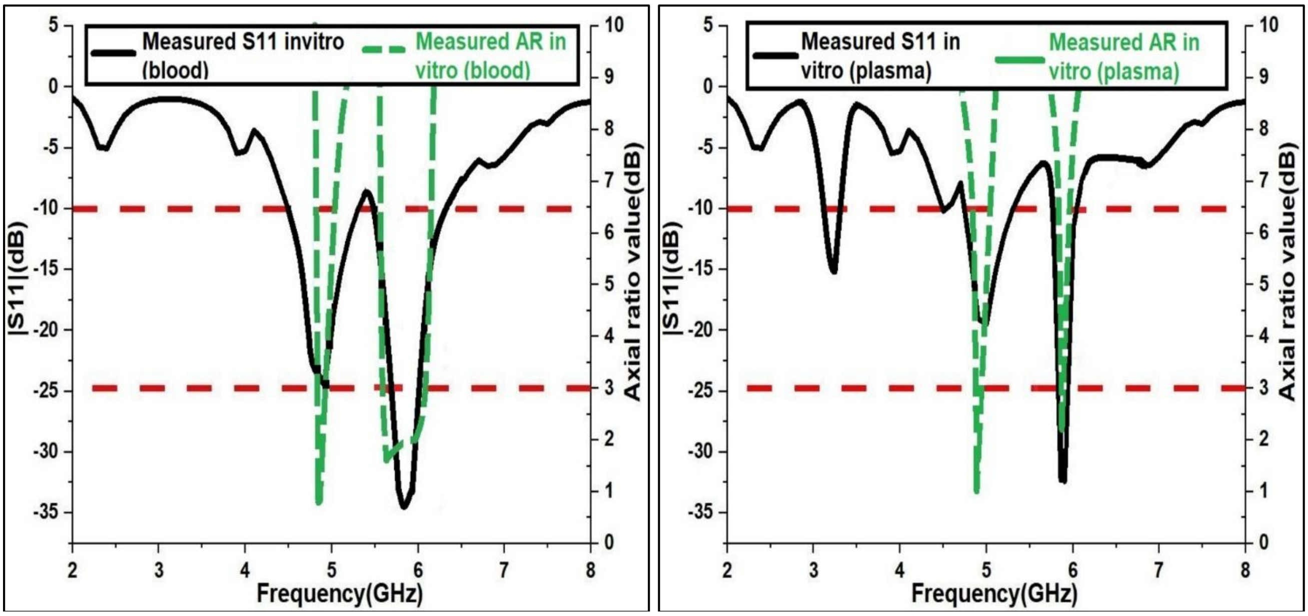
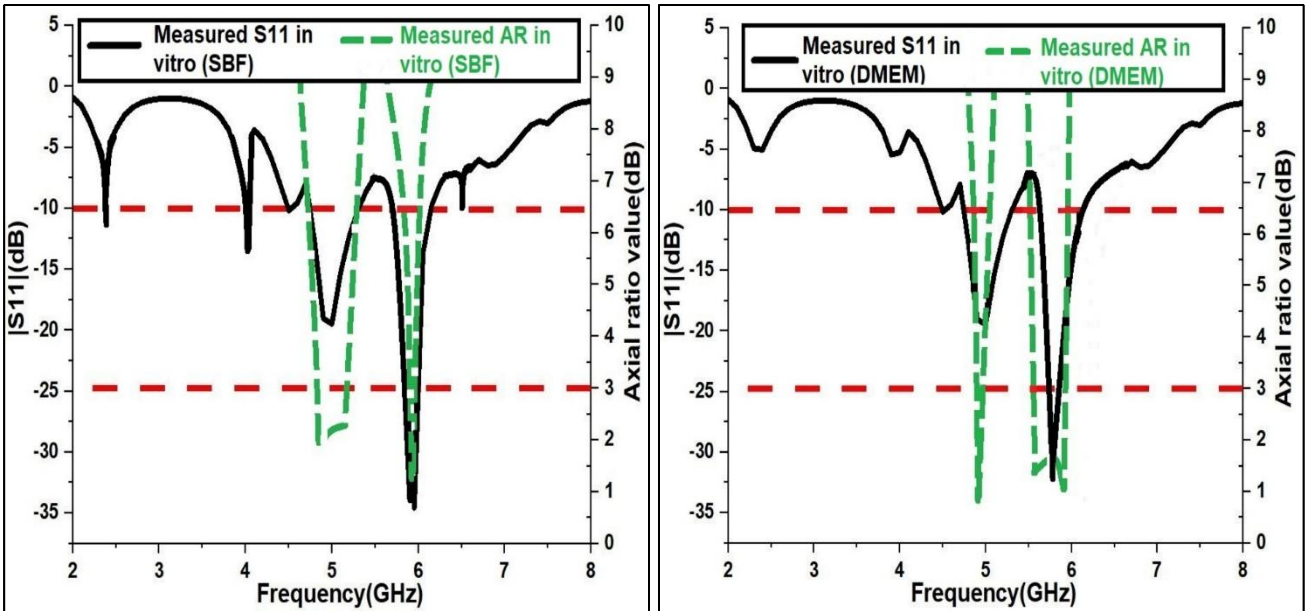


Fig 4: Photographs of the antenna (a) inside the CO_2 incubator, and (b) *in vitro* goat body temperature and CO_2 conditions inside the chamber.



(a) (b)

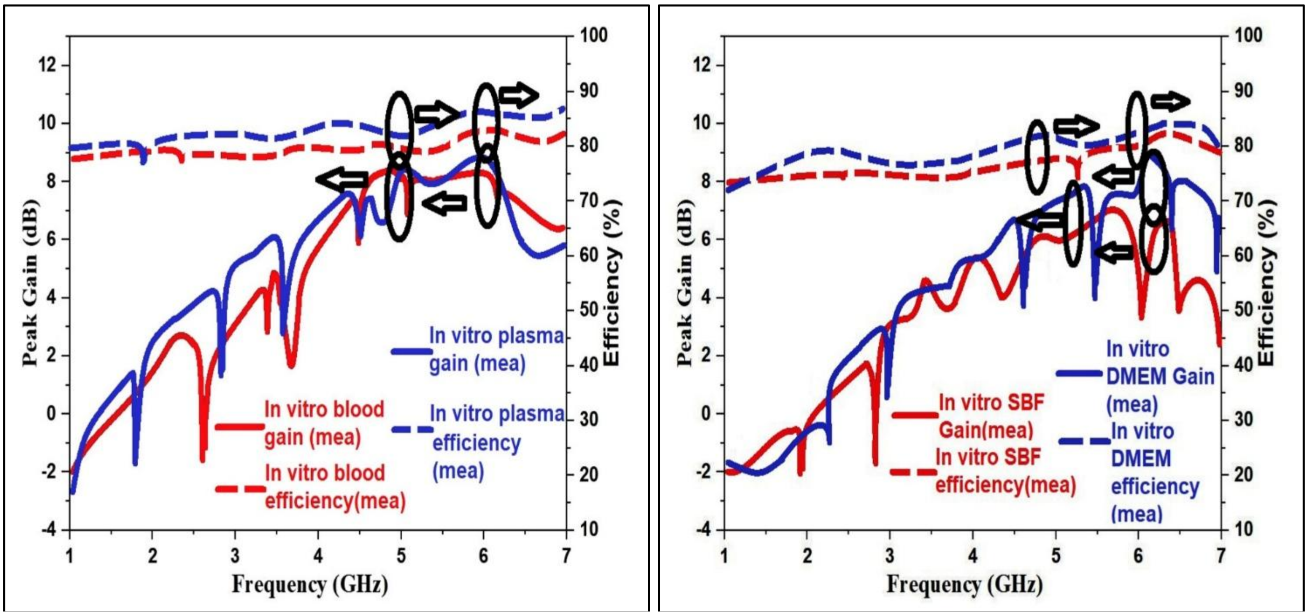


(c) (d)

Fig 5: Measured and simulated S11, and AR *in vitro* conditions.

D-MEM *in vitro* Analysis

Dulbecco's Modified Eagle Medium is a widely used cell culture medium formulated to support the growth and maintenance of various mammalian cells. It contains essential nutrients, vitamins, amino acids, and glucose to promote optimal cell proliferation. As presented in Fig. 3(d), the propounded model is implanted in DMEM and kept in the carbon dioxide incubator to recreate the same possible effects of goat body implantable condition. The antenna was held in the incubator for a period of 8 hours to make sure that the antenna completely absorbs the DMEM. It's operating in the frequencies of 4.55-5.15 and 5.5-6 GHz. As shown in Fig, the AR, where they are under the 3dB line are 4.85-5 and 5.5-6 GHz, and it's covering the ranges of WLAN and ISM bands. As illustrated in Fig. 6(b), the peak gain in the operating frequencies are 8.0, and 8.3 dBi and the efficiency is 81 and 86 percent.



(a) (b)

Fig 6: Measured gain and efficiency of proposed antenna *in vitro* of (a) blood and plasma and (b) SBF and DMEM.

Fig 7: Measurement setup of the *in vitro* blood absorbed antenna for measuring the 5.8 GHz test signal.

4. Biocompatibility Analysis

Corrosion is a chemical phenomenon in which a metal gradually deteriorates due to reactions with its surrounding environment [13-14]. When any metallic material is implanted into the goat body as a bioimplant, various reactions occur between the metal surface and the biological fluids, which lead to the corrosion process. The current study is carried out to understand the electrochemical behavior of the metal in various physiological media such as goat blood and goat plasma [15-16]. Furthermore, SBF and DMEM are also used to study the propounded model behavior under implantable conditions. The Tafel plot is an important technique to study the electrochemical behavior of the metal and to estimate the rate of corrosion by measuring the EMF or voltage developed at the metal surface called corrosion potential (Ecorr). Figure 8 depicts the Tafel curve between corrosion potential (Ecorr) in volts (V) and corrosion current density (Icorr) in milliamperes (mA).

The Anodic slope is given by

$$\text{(1-a)}\ \frac{nF}{RT} \quad (1)$$

The Cathodic slope is given by

$$\text{(a)}\ \frac{nF}{RT} \quad (2)$$

And the corrosion rate (CR) of the metal surface is given by

$$\text{Corrosion Rate-}CR = \frac{3.27X10^{-3}(i_{corr})E_w}{\rho} \quad (3)$$

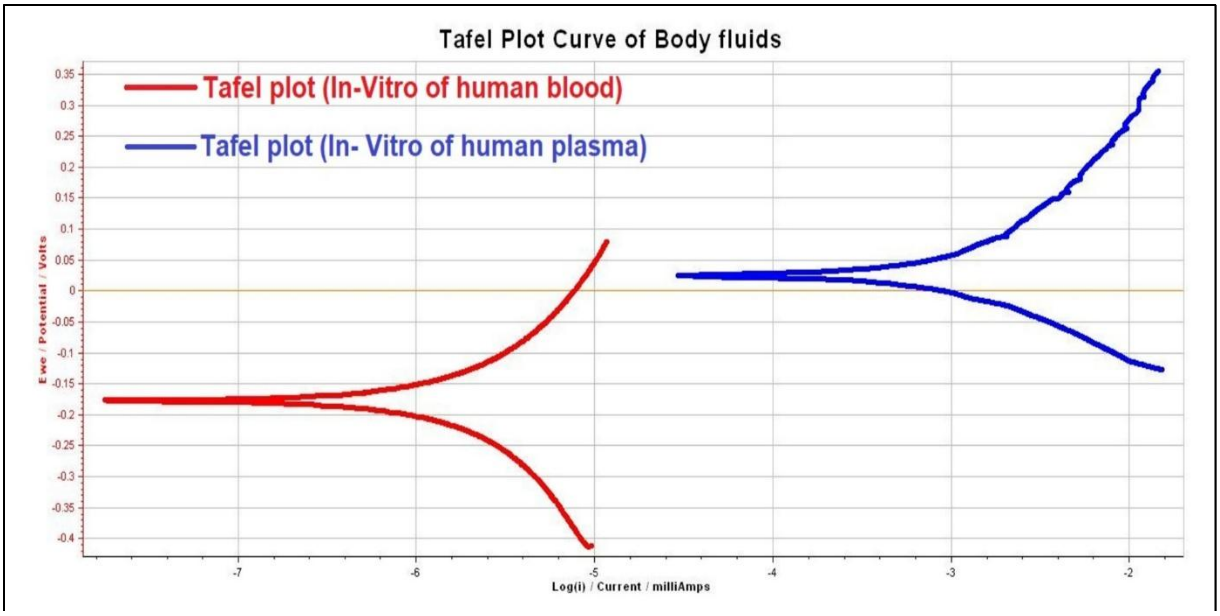
Where

I_{corr} = Corrosion Current density in milliAmps/cm^2

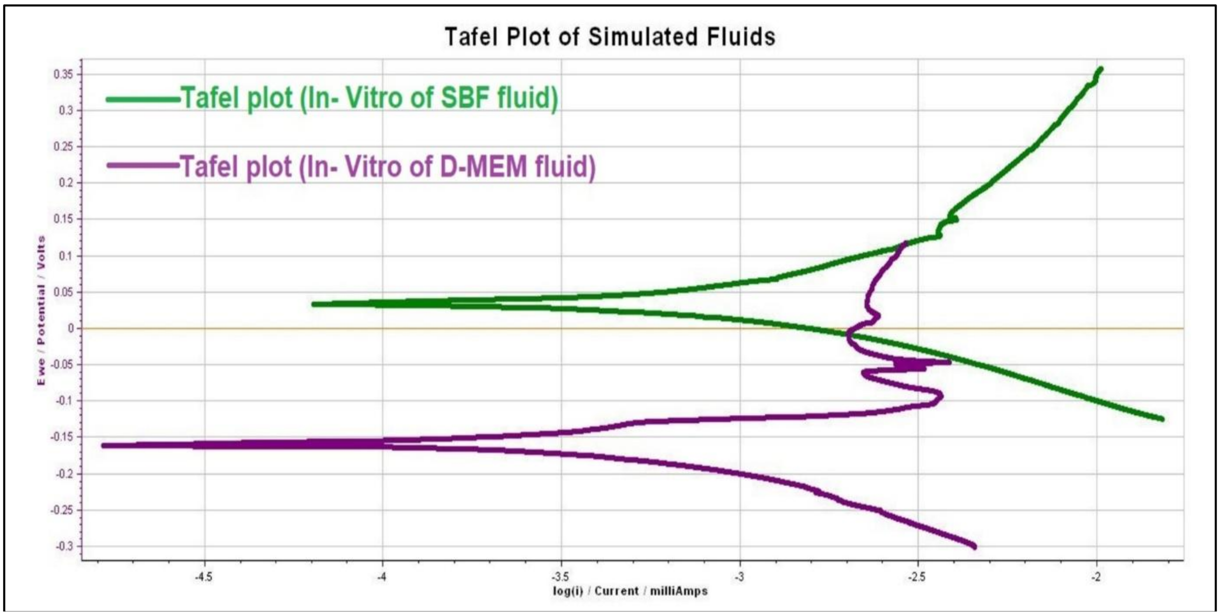
E_w = equivalent weight of the metal in gms

ρ = density of metal in g/cm^3

In this work, the biocompatable performance of the proposed model was further investigated in an implantable environment with different biological and simulated body fluids. Corrosion in various media was measured using the polarization method in BioLogic SAS, SP-300 analyser with a flat corrosion cell and a three-electrode system. A relatively uniform corrosion form was found for the antenna immersed in goat body fluids and simulated media. As can be seen from Table 1, the corrosion current of the antenna in blood and plasma is slightly higher than that in simulated fluid such as SBF and DMEM. However, the annual corrosion rate is extremely low in any cases, indicating that the proposed antenna has a very good corrosion resistance and is suitable for biocompatible implantable biomedical applications.



(a)



(b)

Fig 8: Implantable analysis using Tafel graphs: (a) Bio-fluids and (b) simulated Bio-fluids.

Table 1: Values of Corrosion Rate in different electrolytes by Tafel Curve

SL. No	Electrolyte	Corrosion Rate in mmpy
1	Blood	0.05321
2	Plasma	0.004731
3	SBF	0.003678
4	D-MEM	86.874×10^{-6}

5. Conclusion

A circularly polarized conformal antenna was developed on jute felt material. The proposed antenna is compact with footprints of $20\times16\times1.5$ mm^3 and was resonating at 3.5, 4.9 and 5.8 GHz frequencies in normal dry conditions. The developed model was designed to work in implantable conditions of *in vitro* compatibility in goat body fluids such as blood and plasma. To furtherly analysis, the antenna in the *in vitro* circumstances simulated fluids are also measured for the biocompatibility testing conditions in the carbon dioxide incubator. In all the *in vitro* analysis, the proposed model is operating successfully with circular polarization in the 4.9 GHz WLAN band and 5.8 GHz ISM band applications. The electrochemical behaviour analysis was also performed in the real-time circumstances *in vitro* conditions by considering the blood, plasma, SBF and DMEM as electrolytes. The results from the study show that the jute antenna corrosion rate is low, which is necessary for the biocompatibility. The overall measurements in the anechoic chamber and electrochemical work station furtherly confess the excellent performance of the proposed antenna in normal and *in vitro* implantable conditions.

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