International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-3, January 2020

Design Implantable Antennas with Human Body Effect

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Abstract: ***Implantable antenna devices have made great progress for healthcare services. Amongst the overall components of the implantable device, the antenna is the most important component that exists; it used to transmit the biological data wirelessly from inside the human body tissues to an external receiver. However, the human body tissues' surrounding the antenna decrease the performance of the radiation antenna device, change its characteristics and absorbs most of its radiation. It also limits the size of the implantable device and its battery. Therefore, the design of the implanted antenna inside the human body requires many challenges while meeting many contradictory design parameters at the same time. Therefore, in this research, we mainly focused our spotlight on investigating and designing new antenna structures with robust performance against the human body tissue effect. In this research work, we presented two designs of a dual-band microstrip patch implantable antenna to operate ((401-406 MHz) Medical Device Radio-Communications (MedRadio), 433MHZ 2.45 GHz Industrial, Scientific and Medical (ISM) bands, respectively. This is to satisfy the requirements of data transfer, power saving and wireless power transfer.***

The first design in this paper is a new shape of microstrip patch implantable antennas with meandered serpentine slot, with a single feed point. This shape of design allows us to increase the length of the current path in order to decrease the antenna size and covers MICS and ISM bands with new dimensions of (31 x 25 x 1.63) mm, the measured frequencies range we obtained it's from 378MHz to 450 MHz (17.3%) at the lower band and from 2.46 to 2.68 GHz (8.56%) at the upper band for S11 less than -10 dB. The second simulated design is a compact dual-band Planar Inverted-F Antenna (PIFA) with Open-End Slots on ground with dimensions of (19.8x19.4x1.27) mm the measured frequencies from 325MHz to 407MHzrange at the lower band and from 2.412GHz to 2.482GHz for PIFA antenna, the designs of both antennae constructed and measured using CST and HFSS simulation and measurement setup. We also explained and demonstrated the performance of these antenna designs and the effect of human body tissue on antenna parameters, based on the reflection coefficient in normal and bent conditions.

Keywords : Implantable Antenna; Human body; HFSS Simulator; CST Simulator; Return loss; Standing wave ratio..

Revised Manuscript Received on January 30, 2020.

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I. INTRODUCTION

Recently, Antennas became very popular and important for biomedical telemetry applications and medical area with wireless communication. It develops standards life of people by granting them more relaxed life in the area of health with the help of technological developments; since the introduction of implantable pacemakers in the early 1960s, implantable medical devices have become more and more interesting for healthcare services [1]. Millions of people worldwide depend upon Telemedicine (or wireless medicine) to support and improve the quality of their lives [2]. RF-linked implantable medical devices are already in use for therapeutic applications, diagnostic and monitoring, including temperature monitors, blood-glucose, pacemaker's functional electrical stimulators (FES) and cochlear and retinal implants. This new technology allowed telemedicine and provide healthcare at a distance with a much lower cost [3].

The main goal and the challenges of a healthcare monitoring system with a wireless implantable device is to provide and senses the bio-signals and reliable information from inside the human body and transmit to an external Base Station (BS) with good coverage and quality of monitoring [1]. An example of a healthcare system is illustrated in Figure 1:

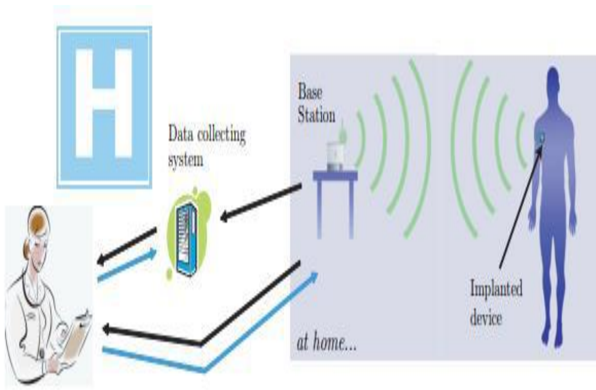


Fig.1: Healthcare-monitoring system with an implantable device working in a Wireless Body Area Network (WBAN) [1].

A biomedical telemetry system, in order to deliver a reliable result and facilitate these functionalities, the implantable device is usually composed a set of several elements that cooperate to give the desired results. This system is illustrated by Figure 2:

Fig. 2: Illustration of wireless implantable systems [4].

1. Base Station: It depends on the application of the implanted antenna; it is usually a PC that is comprises small subsystems:
• A control unit: to manage all the system and to save the data collect and measurements.
• A receiver unit: matched with the antenna in the human body including frequency and polarization.
• Internet modem: (connect many devices to send information to each other).
2. Channel propagation: it is important to ensure the communication quality between the base station and the human body.
3. Bio-Sensors and Bio-Actuators: The types of sensors differ depending on the desired applications and requirements.
4. Energy Source: The power supply, often having the largest volume occupation, sets the lifetime of the apparatus, to avoid the surgeries of replacing or charging the battery, antenna should support the functionalities of wireless power transfer.
5. Insulations (Antenna Package): A housing cap is necessary for any implantable device to avoid any adverse reaction of the living tissues. It is necessary to preserve human health and enhancing data transmission [4].
6. Implantable Antenna: Amongst the overall components of the implantable device, the antenna plays the most significant role in transferring the physiological data from inside the human body. It is integrated inside the human body by surgical means or put on the human body (wearable), depending on the needed application; however, the human body around the antenna changes its overall characteristics and absorbs most of its radiation [5].
Components work to sense the bio-signals, convert them to electrical signals, which are transmitted wirelessly via the antenna [4]. The reliability of the wireless communication link from the implantable device is mainly influenced by the efficiency of the implantable antenna. However, the human body influences the performance of the implantable antenna because it considered lossy, non-uniform and heterogeneous tissues. This effect can be summarized in the following points: Small size and light weight of the implantable antenna.

The (401-406 MHz) Radio communication of Medical Device (MedRadio) and 2.45 GHz Industrial, Scientific and Medical (ISM) bands are mostly assigned for implantable and medical applications, so, miniaturization is required to enable resonance at these bands over the small implantable antenna size.

Biocompatibility of the antenna:

The 433 MHz ISM band has been specified to support the antenna functionalities of wireless power transfer to avert the surgeries of replacement or charging the battery [5, 6]. Hence, the antenna is preferred to work for this band in addition to the 401-406 MHz Med Radio band.
Therefore, this research is mainly focused to investigate and design antennas with a robust performance against the human body.

II. LITERATURE REVIEW

3.1 Electrical Type Antennas

The antenna which has a larger electric near field than magnetic near field classified as electrical antennas [1]. The electrical antennas are oversensitive to the human body losses than magnetic type antennas.
The authors of [6] designed a microstrip patch antenna for (402-405 MHz)
Med Radio and 2.45 GHz ISM bands the size of this antenna was reduced from (179.7 x 228.3 x 1.63) mm3 to (31 x 25x 1.63) mm3, it is still large for medical application furthermore, a narrow bandwidth obtained of only 0.56% of the Med Radio and 0.2% around of 2.45 GHz ISM bands. A spiral planar inverted-F antenna (PIFA) was designed in [7]. Antenna design is shown in Figure 3:

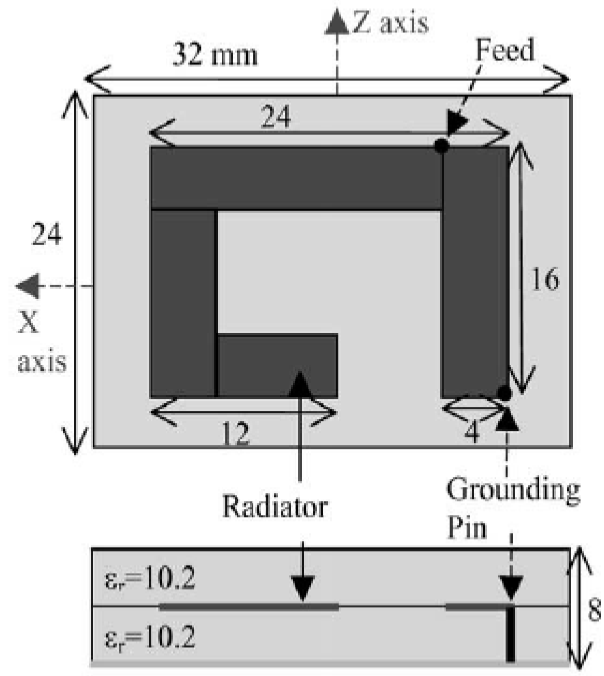


Fig. 3: Top and side views of the antenna proposed in [7].

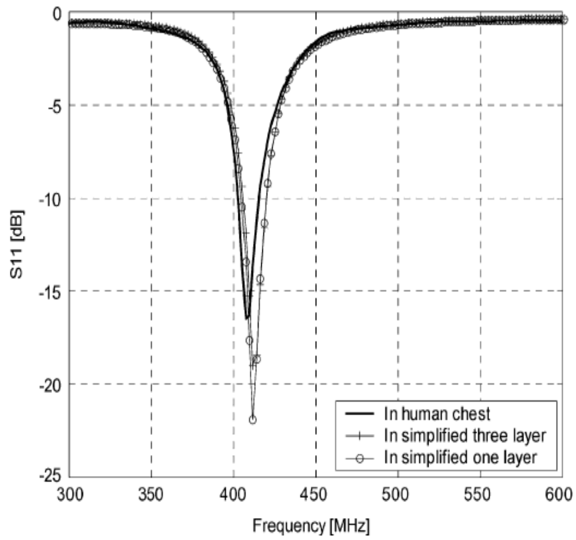


Fig. 4: A reflection coefficient of the spiral PIFA proposed in [7].

The authors of [8] designed a small printed monopole antenna; it was implanted into human breast model for in body communication. The antenna worked for 2.45 GHz ISM band. But, it was large in size, as shown in Figure 5.

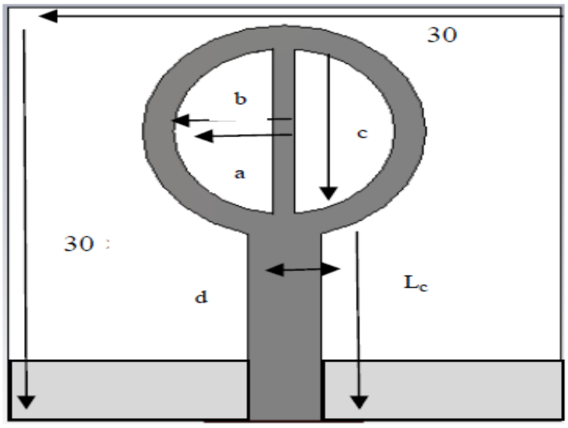


Fig. 5: The monopole antenna in [8]

An implanted CPW fed slot monopole antenna for ISM band applications was proposed in [8] as shown in Fig. 3.4 this antenna was also large.

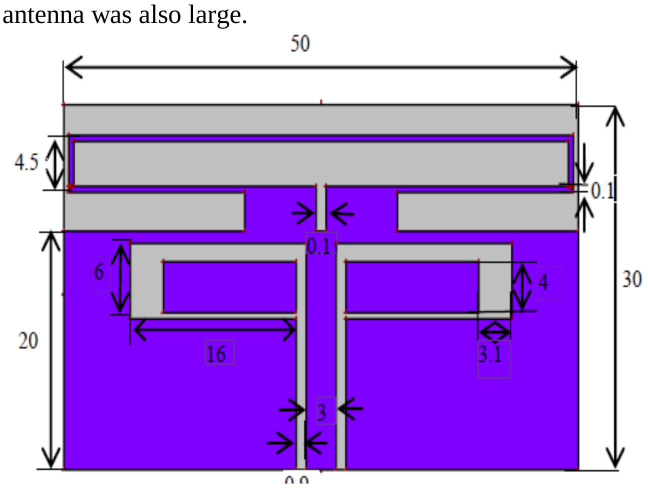


Fig. 6: The monopole antenna deign in [8].

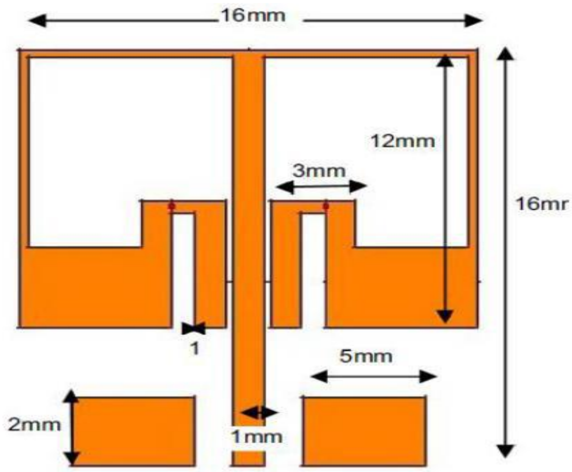
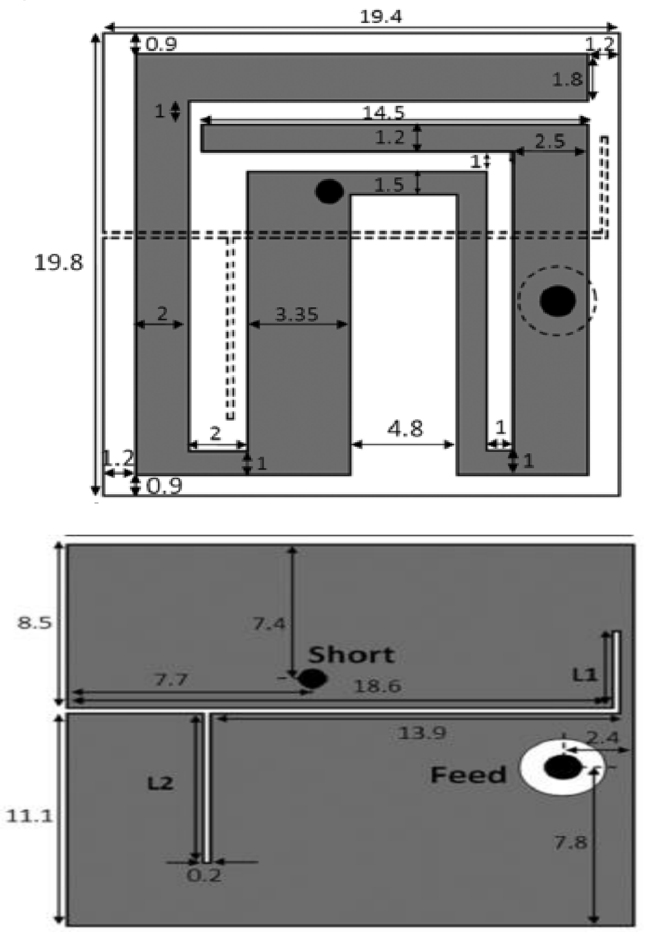


Fig. 7: The monopole implantable antenna structure [9].

In [10], a monopole implantable antenna in the shape of a loop was proposed. This antenna has 16 × 16 × 1 $mm3$ in size.

This antenna worked for the 2.41–2.48 GHz ISM band as shown in Fig. 3.6. It was embedded in a substrate of Teflon and it had a narrow bandwidth around 2.45 GHz.

In [10], the authors designed a slot planar inverted-F antenna for dual bands (356- 610 MHz and 2.45 GHz ISM) as shown in Fig. 3.7. The antenna size is (19 ×19×1.27) $mm3$which is quite large for implantable application. The antenna reflection coefficient is shown in Figures 8: a, b and c:



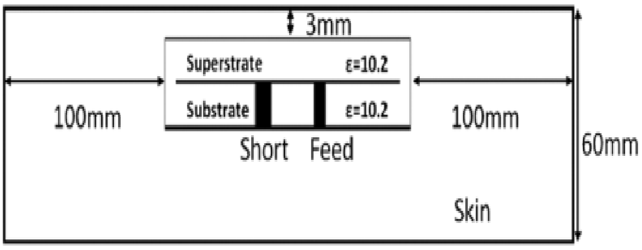


Fig. 8: Slot PIFA antennas (a) Top, (b) bottom and (c) side views in [10].

III. ANTENNA DESIGN RESULTS AND DISCUSIONS

we will discuss two designs of a dual-band microstrip patch implantable antenna, these designs have been suggested to operate in Medical Implant Communication Services (MICS) (402-406 MHz), within 433 MHz wireless power transfer, Scientific and Medical (ISM) (2.4 - 2.48 GHz) bands, these designs simulated by two programs high frequency structure simulator (HFSS) and Computer Simulation Technology (CST) to evaluate the performance of the proposed antenna.

A general design procedure applied for both designs a meandered serpentine shape and inverted PIFA of microstrip patch implantable antenna. The design is determining requirements and limitations. The first required for both design is the antenna must be well matched which means ($S11\leq$ -10 dB) at MICS bands and at ISM bands. The second requirement is comparatively large radiation efficiency and gain.

The fundamental restriction for both designs is the physical size; which should be enough small for implantable utilizations and applications.

III.1 Antenna's Width and Length

We use the following reference equations to calculate the patch dimensions and design, a rectangular patch with the correct width and length should both be obtained [11]:

1. The width W leads to good radiation efficiencies and controls both the input impedance and the radiation pattern. The wider the patch becomes, the lower the input impedance. It is calculated using :

$$W=c2fr\sqrt{2\varepsilon r+1} \qquad (1)$$

2. The length of the patch controls the resonant frequency and its obtained using:

$$L=c2fr\sqrt{\varepsilon eff}-2\Delta l \qquad (2)$$

$$Leff=c2fo\sqrt{\varepsilon reff} \qquad (3)$$

The effective dielectric constant of the microstrip antenna and the extension of the length ΔL are determined using:

$$\Delta L=.412h\varepsilon eff+.3wh+0.264\varepsilon eff-.258wh+0.8 \qquad (4)$$

$$\varepsilon eff=\varepsilon r+12+\varepsilon r-121\sqrt{1+12hw} \qquad (5)$$

Where:

$\varepsilon reff$: is the effective dielectric constant.

εr: is the dielectric constant of substrate.

h: is the dielectric substrate height.

W: is width of the patch.

$Leff$: is effective length

L: is actual length and ΔL is a distance when the patch length has been extended on each end.

C: Free-space velocity of light.

III.2 Microstrip Patch Implantable Antenna

The first design is a dual band microstrip patch implantable antenna with meandered serpentine shape. This antenna has been designed to operate in MICS (401-406 MHz) and ISM (2.4 - 2.48 GHz) bands.

Based on the previous studies, researches and the available parameters, we design a meandered microstrip patch antenna, which is characterized by simplicity and effectiveness of performance. This new type of antenna has been designed using HFSS and CST simulation and measurement in order to get accurate results and simulation.

The proposed meandered microstrip patch antenna design size is 31mm x 24 mm x 1.63 mm explained in the following Fig. 4.2 and Table. 4.1. Which show structure view with diminutions of the meandered of the proposed antenna.

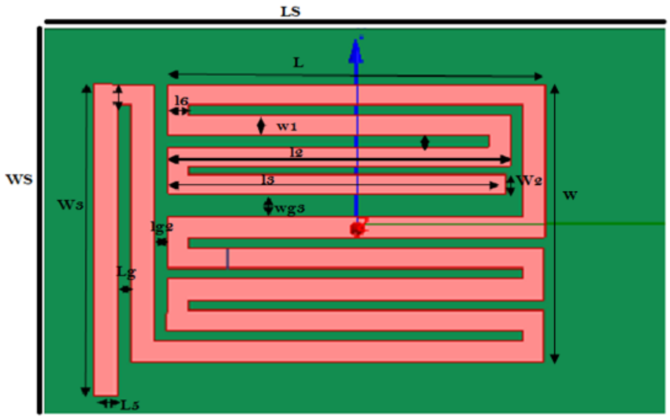


Fig. 9: Proposed meandered serpentine miniaturized dual-band patch antenna.

Table 1: The design parameters and dimensions.

Parameter	Dimension(mm)	Parameter	Dimension (mm)
Ls	51	Ws	35
L	31	W	24
L4	2	W1	1.8
Lg2	1	W2	1
Lg	1	W3	28
L5	2	Wg2	1.5
L3	26	Wg	1
d	5	hskin(thickness)	3
h	1.63	hfat(thickness)	3
		hmuscles(thickness)	16

Now, we will review the results of the design through the simulation software HFSS and CST Microwave studio. The results obtained when the design implanted inside and outside the tissues of the human body, then investigated its impact of characteristics on the antenna. We choose the values of dielectric constant for the meandered srpentine design as in the following table:

Table 2: Dielectric Constant for Meandered design

Materials	**Dielectric Constant(εr)**	**Conductivity (S/m)**
Substrate(Rogers 3210)	10.2	.004
Fat	11.2	.0808
Muscle	57.1	.797
Skin	46.7	.63

IV. SIMULATION AND RESULTS

The antenna was designed and simulated by using HFSS and CST for purpose of validation of the simulation results, both obtained results are proposed by illustrated to operate in two environments, the first environment when the antenna operates in free space where all the super strate 46 and the dielectric, loss, and conductivity of the human tissue were ignored. The second environment when the antenna is simulated in a multilayer body model, the body model comprises three layers; namely, skin, fat, and muscles [5].

IV.1 Return Loss S11:

The reflection coefficient ($S11$) of simulated antenna in free space is shown in the following figures using CST, HFSS and MATLAB code the measured data have been plotted (frequency [GHz] versus $S11$ [dB]) as shown in Figure 10:

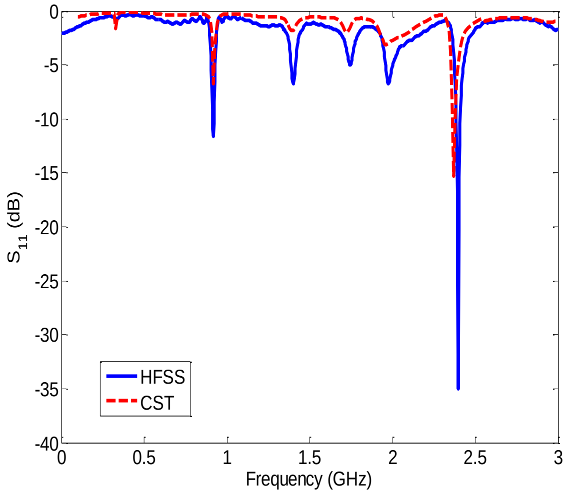


Fig.10.The reflection coefficient of the meandered antenna by CST and HSS in free space

After implanting the microstrip patch antenna in the real living human body tissues, mistuning will probably happen, the antenna is simulated in a multilayer body model that is shown in Fig. 4.4. The body model comprises three layers; namely, skin, fat, and muscles. The proposed antenna is simulated at the centre of the fat layer Figure 11.

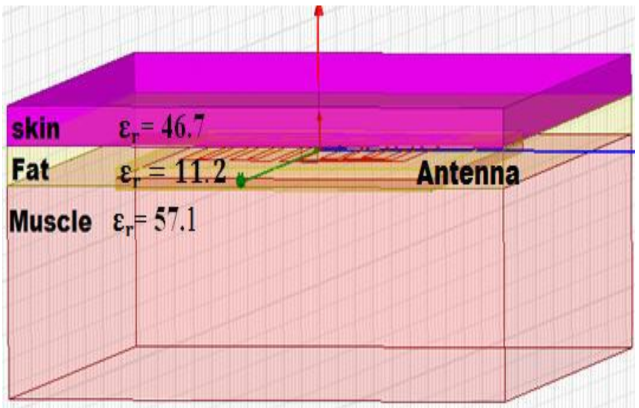


Fig. 11: The antenna is embedded and simulated in a multilayer body model.

The simulated antenna reflection coefficient (S11) is shown in Figure 12. It can be seen from the figure that the antenna has obtained a reflection coefficient (S11) of -17.8dB at 403MHz at the lower band and of -10.77dB at 2.48GHz.

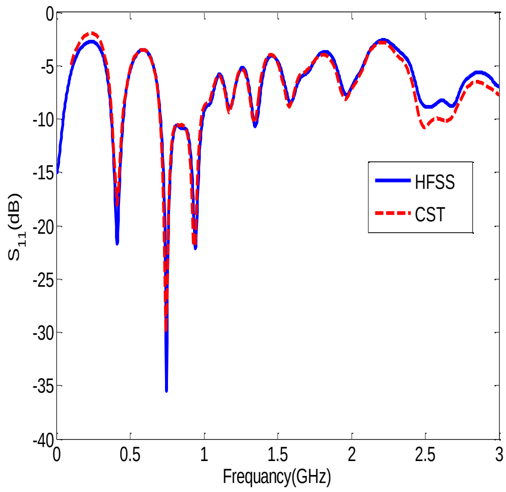


Fig. 12: Simulated reflection coefficient of the meandered antenna implanted inside the tissue of human body by CST and HFSS

This design operating at ISM upper band and at MICS the lower band, the return loss magnitude $|S11|$ has been simulated in the range (0GHz-3GHz) and the measured frequencies range from (378-450) MHz (17.3%) at the lower band covering the MICS band from (401-406) MHz within the ISM band at 433 MHz and from (2.4 -2.68) GHz (8.56%) at the upper band for ($|S11|<-10\ dB$). We can calculate the band width in upper and lower rang according to the simulation results by equation (6).

Bandwidth: for the lower band:

BW=[(450−378) /414]×100%=17.3%

Bandwidth: for the upper band.

BW=[(2.46−2.68) /2.57]×100%=8.56%

The simulated antenna reflection coefficient ($S11$) is shown in Figures (10,12) It can be seen from the figure that when the antenna implanted inside the tissue of the human body the matching improve and the antenna has obtained a reflection coefficient ($S11<-10dB$). It can be seen from the figures of the simulated results, the HFSS and CST show good agreement antenna.

IV.2. Input Impedance

Impedance matching is one of the most challenging factors, as it is required to have a reflection coefficient $|S11|<$ -10 dB. The input impedance of the antenna around the two frequencies (372 MHz and 2.41 GHz) is plotted in Fig. 4.10. It is indicated that around the first resonant frequency, the antenna presents a maximum real part of 34 Ω with a zero imaginary part; while around the second resonant frequency, the maximum real part is 24 Ω when the imaginary part is 0. This figure shows the resonant behavior of the structure. The real part resistance cancels out the imaginary part.

This is desired to keep the reflected power small even if detuning happens in the real human body.

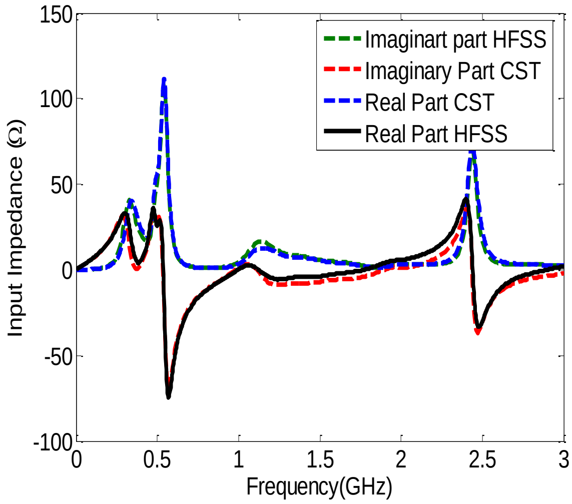


Fig.13: Z11 (Real and Imaginary) parts of the input impedance in the simplified body model.

IV.3 VSWR of the Designed Antenna

The standing wave ratio of this design is cleared in Figure 14. Standing wave ratio (SWR) is a measure of impedance matching of loads to the characteristic impedance of a transmission line or waveguide. The SWR directly corresponds to the magnitude of Γ; The voltage standing wave ratio is then:

$$VSWR = |Vmax|/|Vmin| = (1+|\Gamma|)/(1-|\Gamma|) \quad (6)$$

Since the magnitude of Γ always falls in the range [-1,1], the SWR is always greater than or equal to unity[6]. For our design, the VSWR value at 403MHz equal to 1.24 and 1.53 at 47GHz.

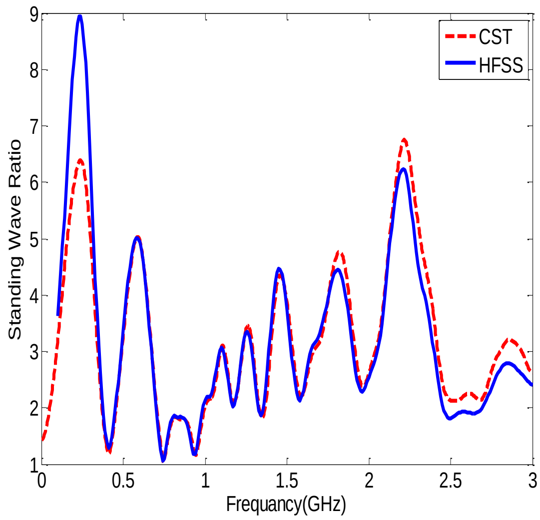


Fig. 14: The standing wave ratio of the antenna in the simplified body model.

IV.4 Design of Planar Inverted-F Antennas (PIFA)

The second design in this thesis is a dual-band implantable Planar Inverted-F Antennas (PIFA) structure, this type of antenna has been designed using HFSS and CST simulations, in this section, we will review the results and measurements of PIFA design when it implanted inside the human body tissues and outside of it. Figure 15 shows the proposed PIFA design structure with diminutions symbols.

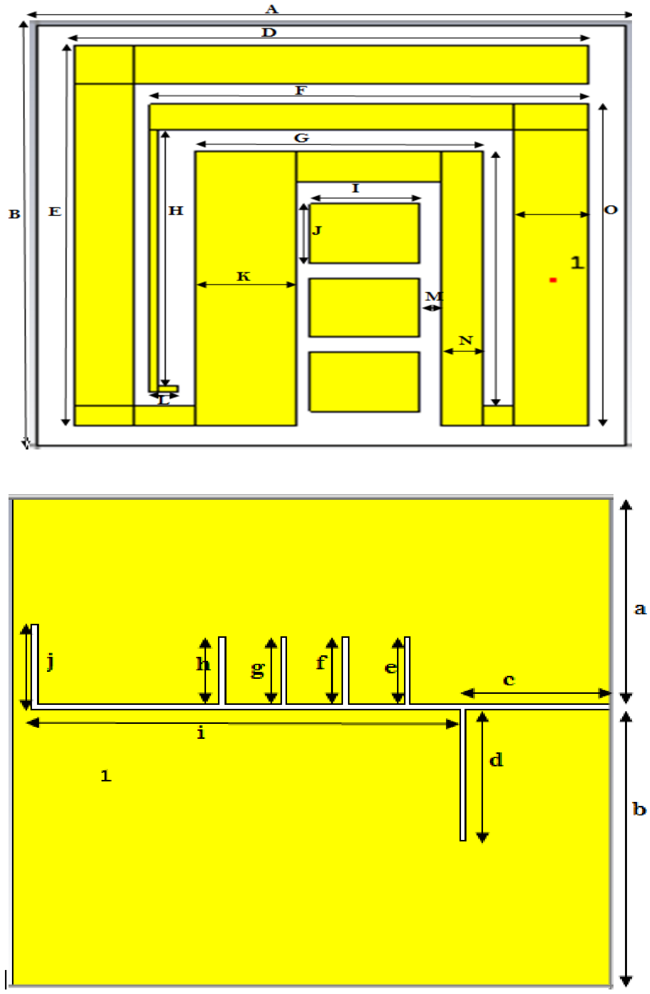


Fig. 15(a) Top and (b) bottom views of PIFA structure of the proposed antenna.

Table 2: shows the dimensions of the PIFA design

Parameter	Dimension(mm)	Parameter	Dimension (mm)	Parameter	Dimension
A	19.4	L	1	d	5.3
B	19.8	M	0.9	e	2.86
D	18.2	N	1	f	2.86
E	18.9	O	15.2	g	2.86
F	14.5	P	2.5	h	2.86
G	9.5	a	8.5	i	13.9
H	12.4	b	11		
K	3.35	c	6.5		

From the Figure 15 the design dimensions of PIFA is 19.8 mmx19.4x mm x1.27 mm, the six open-end slots created in the ground plane in order to tune the resonant frequencies at the lower band to obtain optimal bandwidth.

In this thesis, we choose the values of dielectric properties and conductivity from [12]. The table 3 shows the dielectric properties for each layer that use in proposed design.

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DOI: 10.35940/ijitee.C8874.019320
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Table 3. Characteristics and dielectric properties of the designed PIFA design

	Material	Permittivity εr	conductivity σ(S/m)
skin	**At 402 MHz**	46.74	.69
	At 2.45 GHz	38.06	1.44
Rogers 3010		10.2	0.95
Copper		1	5.80×107

The antenna design has substrate and super strate layers with a thickness of 0.635 mm for both layers. The super strate is needful for this design in order to reduce the losses that come in from the tissues of the human body and to improve the antenna gain; the superstrate is also needful for biocompatibility. In order to decrease the antenna size in this design, we put a shorting pin with 0.9mm diameter to increase the electrical length and minimize the antenna size. We create six open-end slots with a regular width of .2mm craved in the ground plane; these slots also widen the bandwidth.

Simulation and Results:

This design operating at ISM upper band 2.45 GHz and by adding six open-end slots in the ground plane we created resonant frequencies at the lower band covering the MICS band at 402MHz within the ISM band at 433MHz. We can calculate the bandwidth in upper and lower rang according to the simulation results by equation (6). At the lower band the range of frequencies from 321 MHz to 406 MHz and at the upper band the range of frequencies from 2.41GHz to 2,482 GHz for |S11| less than -10 dB.
Bandwidth: for the lower band:
BW= $((\mathbf{406-321})\ /\ 363) \times 100\%=23.3\%$
Bandwidth: for the upper band:
BW= $((\mathbf{2.482-2.41)/2.446})\times 100\%=2.9\%$

Return Loss:

The reflection coefficient ($S11$) of simulated antenna in free space and when is shown in the following figure. It is seen that the matching at the lower and upper band needs to be improved for the antenna in free space.

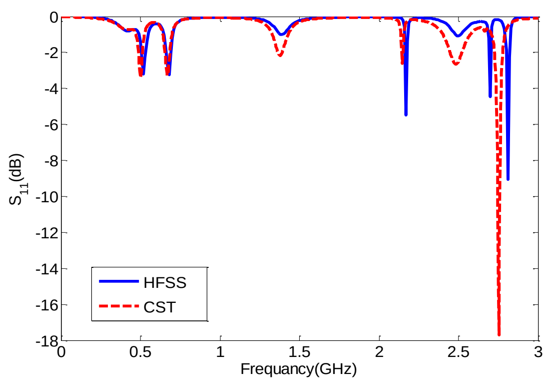

Fig. 16: Simulated reflection coefficient of the proposed antenna in free space by CST and HFSS

The Figure 17 shows the geometry of the simplified multilayer human body that simulated in a multilayer body model. The body model comprises three layers; namely, skin, fat, and muscles. The proposed antenna is simulated at the centre of the skin layer

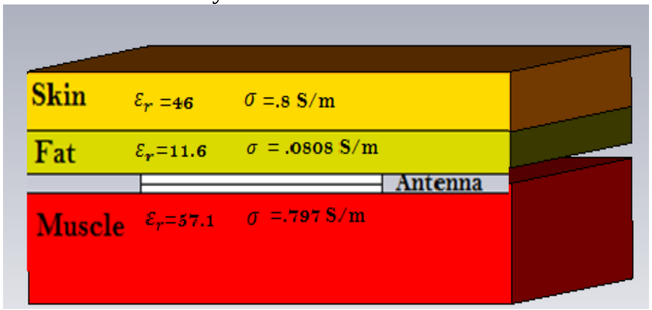

Fig. 17: shows the geometry of the PIFA antenna simplified multilayer human body model.

The simulated antenna reflection coefficient ($S11$) when the implantable antenna implanted inside the tissue of the human body is shown below in Figure 18.

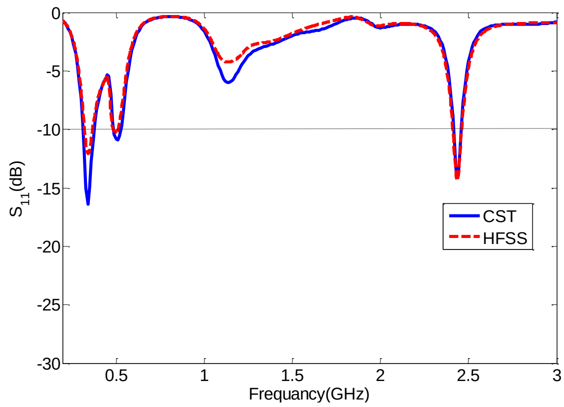

Fig. 18: The reflection coefficient (□11) of simulated antenna inside the tissue of human body by CST and HFSS.

It can be clearly seen that a noticeable frequency shift to the left occurred (decrease infrequency) in both MICS and ISM bands. For the lower frequency, the return loss magnitude increased and the frequency went out of the desired range. For the higher frequency band, the return loss went low and the bandwidth has widen, so, even though the peak frequency went out of the desired range, the bandwidth still covers our desired frequency range.
These obtained results are directly related to the dielectric property of the skin whose dielectric constant is too high compared to the free space, and its thickness is around 1.5 mm. This difference in both thickness and dielectric property affects the radiation performance and causes a decrease in the operating frequency under the skin, since the velocity of the electromagnetic wave is higher in the small dielectric constant material thus yielding longer operating wavelength.

V. Conclusion

The implantable antenna design is difficult and demanding which is mainly due to the complicated environment of propagation because the human body tissues surrounding the antenna decrease the performance of the radiation antenna device,

change its characteristics and absorbs most of its radiation.
In this thesis, we proposed two implantable antenna designs , the first design a dual-band microstrip patch implantable antenna with meandered serpentine shape and the second one is a dual-band implantable Planar Inverted-F Antennas (PIFA) structure, both of these antennae are proposed for the 2.45 GHz and 433 MHz ISM bands and (401-406) MICS bands the two antennae are good designs for implantable applications because of comparatively small size, good radiation characteristics, achieved the antenna matching (S11<-10 dB) for both designs, cover (401-406)MICS band and 433 MHz 2.45GHz ISM band, which supports wireless power transfer, expansion the communication range.

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