PLANER INVERTED – F ANTENNA DESIGN FOR MEDICAL IMPLANT APPLICATION AT ISM 900 MHz

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Abstract
Radio – linked medical implant are recently attracting significant research interest. A key component of implantable medical devices which plays a major role in their compactness and general performance efficiency is the antenna. Hence, innovation in wireless body area network for telemetry applications is creating a demand for higher bandwidth and resilient implant links, and this in turn is driving the development of implantable antennas. The design of Planer Inverted – F Antenna (PIFA) based on transmission line model was made for medical implants operating at ISM 900MHz. The designed antenna was simulated using High Frequency Structural Simulator. This antenna which resonated at 902MHz frequency had a return loss of $-7.61dB$*, impedance bandwidth of* 2.2%*, a radiator size of* $34\text{mm} \times 17\text{mm}$ *and radiation efficiency of* 1.44%*. The simulated result of electric field distribution E (0.12dB) is far below the reference level set for the general public by ICNIRP. The performance characteristics of the proposed PIFA reveal that it can be used as implantable antenna for medical implants. However, effective miniaturization technique need to be employed in the design to improve the radiation efficiency of the designed antenna.*

Keywords: PIFA, Medical implant, Return loss, Radiation efficiency, Specific Absorption Rate (SAR).

Introduction
Advances in technology have enhanced the use of implantable medical devices operating in radio frequency range in diverse medical applications. Medical body area network (MBAN) – a network of body implanted electronic medical devices – has tremendously improved health care, therapy and diagnosis. Integrated communication from different in–body implants and on– body sensors can facilitate hearing for the deaf, sight for the blind and mobility for the lame. (Higgins, 2005).

Active medical implants are electronic devices that are surgically implanted inside the body. They have been developed to treat a wide range of ailments (Anders, 2004) such as

i. heart pacemakers which makes the heart beat in orderly manner
ii. brain pacemakers for the treatment of Parkinson's disease
iii. Nerve signal recorders for use with robotic prosthesis
iv. Implantable drug pumps
v. Cochlea implants and so on

All these communicate with the outside world by radio. Radio communication makes the system usable at longer ranges. This telecommunication which enabled telemetry offers the following benefits:

a. The data of the patient can be read ahead of time before he/she enters the doctor's office thereby reducing the checkup time.
b. Patients who require very frequent checks may not necessarily be confirmed to the hospital where home care unit is available which can be made to communicate with medical implants and sends regular reports to the doctor (health care provider) in the

hospital via internet or telephone system. This can help to decongest the hospital and also gives more comfort to the patent who will be at the comfort of his/her own home.

c. Since patients may not need to get to hospital regularly the cost of health care is reduced.
d. Moreover when anything goes wrong either with the state of health of the patient or with the implant, the doctor receives the information immediately giving him/her enough time to proffer solution before the patient gets to the hospital.
e. Implantable devices can also facilitate the physical and mental burden to patients since their employment is able to reduce the number of visits of doctors to diagnose patients.
f. These devices can communicate without a wire piercing the skin thereby reducing the risk of infection in medical diagnosis (Tamotsu et al., 2007).

The antenna enables bidirectional wireless communication between the Implantable Medical Device (IMD), the exterior monitoring and control equipment (Asimina and Konstantina, 2013). In medical implant applications, it is of paramount importance to minimize antenna size and retain sufficient impedance bandwidth to cover the required operating frequency with a minimal loss in both body tissue and antenna structure. The antenna that meets this requirement is the Planer Inverted–F Antenna (PIFA). It is a self- resonating antenna with purely resistive impedance at the frequency of operation, hence, does not require conjugal circuit between the antenna and the load reducing both cost and losses. Therefore, this paper considers the design of PIFA for radio–linked medical implant that will satisfy the above requirements.

Antenna Performance Parameters

The performance of the implantable antennas and the entire system are quantified using sets of technical requirements such as the voltage standing wave ratio (VSWR), return loss, gain, quality factor, bandwidth, antenna efficiency and so on. These performance parameters are discussed briefly as follows:

Voltage Standing Wave Ratio (VSWR)

Input matching can be described either by return loss or VSWR. VSWR is a value describing the ratio of the maximum value to minimum value of the electric field intensity of a standing wave. It is basically a measure of the impedance mismatch between the transmitter and the antenna. The VSWR is given as

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} = \frac{|Emax|}{|Emin|} \qquad 1 \leq VSWR < \propto \tag{1}$$

where Γ refers to the voltage reflection coefficient i.e. the ratio of the reflected wave to the forward wave expressed in volts (Makarov, 2002). When VSWR = 1, no standing wave appears and all power is transmitted. If VSWR is large, the Γ is close to one and the antenna does not transmit any power. Since the antenna is a one-point component, Γ is proportional to the S_{11} or return loss.

Return Loss (S_{11} parameter)

The return loss or reflection loss measures the effectiveness of the power delivery from the transmission line to the antenna (Edling, 2012). Hence it is a parameter that indicates how well the matching between the transmitter and antenna has taken place. A graph of S_{11} of an antenna versus frequency is known as the return loss curve. For optimum working, such a graph must show a dip at the operating frequency and have a minimum dB value at this frequency (Makarov, 2002).

$$\text{Return loss} = -20log|\Gamma| \text{ (dB)} \tag{2}$$

Bandwidth (BW)

The bandwidth of an antenna is defined as the range of useable frequencies within which the performance of the antenna with respect to some characteristics conforms to a specified standard (Balanis, 1997).

The impedance bandwidth of a narrowband antenna is defined as the percentage of the frequency difference over the center frequency (f_0) given mathematically as (Edling, 2012)

$$\text{BW narrowband (\%)} = \left[\frac{f_2 - f_1}{f_0}\right] \times 100 \qquad (3)$$

where f_0 is the center (resonant) frequency , f_1 and f_2 is the frequency when the center frequency has dropped 3 dB from the maximum value.

Due to the mismatch of the antenna, a limitation criterion is usually set to define a specific bandwidth. This criterion is not fixed since every antenna does not require the same capability. However, for most of the mobile communication antennas, the limit is ruled by return loss (S_{11}) parameter (Saisset and Travers, 2009). The limit is either $S_{11\ max}$ = -10dB or S_{11max} = -6dB at the borders of the frequency band which correspond to a power reflection of 10% and 25% respectively (Gustrau and Manteuffel, 2006).

Quality factor (Q-factor)

Q-factor is a parameter that describes how much power that transform as losses in the system. A high *Q* factor indicates a lower rate of energy loss relative to the stored energy as (Edling, 2012)

$$Q = 2\pi f_0 \frac{Energy\ stored}{Power\ loss} = \frac{f_0}{f_2 - f_1} = \frac{f_0}{Bandwidth} \qquad (4)$$

It is used to describe antenna as a resonator and quantifies the potential bandwidth of an antenna. Higher value implies a sharp resonance and narrow bandwidth (Ikram, 2010).

Gain

Antenna gain is a parameter which is closely related to the directivity of the antenna. The gain is the amount of power that can be achieved in one direction at the expense of the power lost in the others (Ulaby, 1999).

Radiation Efficiency

The efficiency of a handset antenna is the ratio of the total power radiated by the antenna to the forward power available at its terminals. This parameter takes into account the amount of losses at the terminal of the antenna and within the structure of the antenna. The losses include; reflections because of mismatch between the transmitter and the antenna and I^2R losses (conduction and dielectric) (Balanis, 1997).

Specific Absorption Rate (SAR)

SAR is an index that qualifies the rate of energy absorption in biological tissue expressed in W/kg. SAR measures the amount of heat generated in the tissue surrounding the implant antenna. It is generally taken as an average value over some portion covered by the antenna power. It is defined as

$$SAR = \frac{\sigma}{2\rho}|E^2| \qquad (5)$$

where σ is conductivity of the tissue (S/m), ρ is density of tissue (kg/m) and E is electric field intensity (V/m).

Safety levels are established for SAR parameter and threshold are also established for other em quantities such as power density, electric and magnetic field intensities which are easily measured outside the body. International bodies responsible for setting these safety levels include; International Commission on Non ionizing Radiation Protection (ICNIRP), Federal Communication Commission (FCC) and International Electrical and Electronic Engineers (IEEE). Table 1 shows the reference threshold set by ICNIRP for 900MHz and 1800MHz for general public.

Table 1: ICNIRP reference levels for general public exposure to e.m field

Frequency	Limit for electric field (V/m)		limit for power density W/m^2	
	Public	Occupation	Public	Occupational
900MHz	41.25	90.00	4.5	22.50
1800	58.30	127.28	9.0	45.00

Source: Osuagwu and Emmanuel (2013)

PIFA Design Considerations

PIFA consists of five main components which are; ground plane, patch (radiator) short plate, feed pin and dielectric substrate as shown in figure 1.

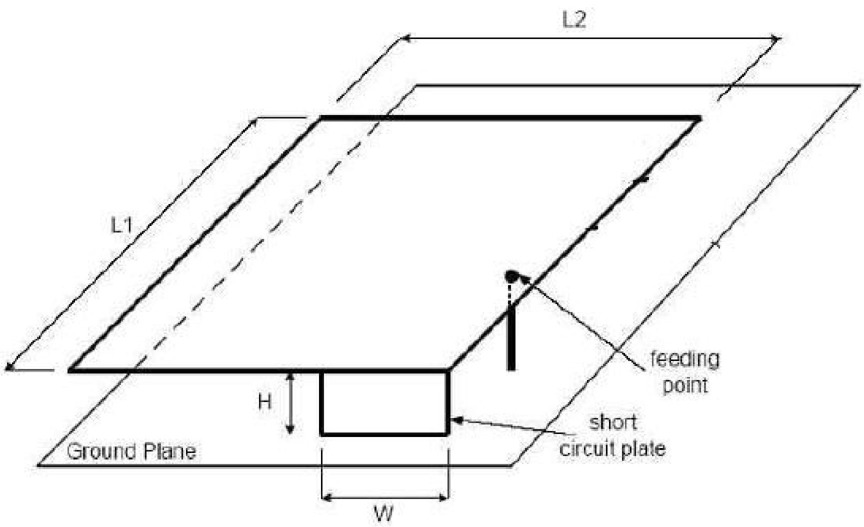

Fig. 1: Features of PIFA

In PIFA, a plate forms the shorting pin as shown in Fig.1. Here L_1 is the patch length and L_2 is patch width. The feed is at a distance of D from the shorting pin and height h from the ground. The patch is on a dielectric with permittivity ε_r. PIFA resonant frequency is dependent on the width (W) of the short-circuit plate. If $W = L_2$, the entire width of the patch is equal to that of the shorting pin and the resonant will have a maximum radiation efficiency (Shaheen et al, 2013).

By transmission line model, when the width of the short circuit plate W is equal to the width of the planar element L_2, this corresponds to the case of short circuit microstrip antenna (MSA) which is a quarter-wavelength antenna. That is

$$W = L_2 \;\; => L_1 = \frac{\lambda}{4} \tag{6}$$

The effective length of the MSA is $L_1 + H$, where H is the height of the short circuit plate. The resonance condition then is expressed as

$$L_1 + H = \frac{\lambda_0}{4} \tag{7}$$

where $\lambda_0 = c/f$ is the wavelength (Huynh, 2000). Hence resonant frequency (f) associated with $W = L_2$ is

$$f_1 = \frac{c}{4\,(L_1+H)} \tag{8}$$

where c is the speed of light.

For W =0, a short-circuit plate with a width of zero can be physically represented by a thin short-circuit pin. The effective length of the circuit is $L_1 + L_2 + H$. For this case, the resonant condition is expressed as (Huynh, 2000)

$$L_1 + L_2 + H = \frac{\lambda_0}{4} \quad => \frac{c}{4(L_1+L_2+H)} \tag{9}$$

Therefore the resonant frequency that is part of the linear combination associated with the case of $0 < W < L_2$ is given as (Yves – Thierry et al., 2009)

$$F_2 = \frac{c}{4\,(L_1+L_2+H-W)} \tag{10}$$

Equation (10) holds for air dielectric with ε_r = 1. When a dielectric material other than air is employed, the resonance frequency is given as

$$f_r = \frac{c}{4\sqrt{\varepsilon_{eff}}(L_1+L_2+H-W)} \tag{11}$$

where ε_{eff} is the effective permittivity of the substrate material between the radiating patch and the ground plane (Yves – Thierry et al., 2009). The approximate value of ε_{eff} is given as
(Yves – Thierry et al., 2009)

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} \tag{12}$$

For fixed radiating patch lengths, the resonant frequency increases as W decreases. Optimum performance is achieved when the ratio of L_1 and L_2 is 2:1(Yves – Thierry et al, 2009) i.e. $L_1 = 2L_2$. When $H = W$ and $L_1 = 2L_2$, equation (11) reduces to

$$f_r = \frac{c}{4\sqrt{\varepsilon_{eff}}(3L_2)} \Rightarrow \quad f_r = \frac{c}{12(L_2)\sqrt{\varepsilon_{eff}}} \tag{13}$$

$$\therefore \quad L_2 = \frac{c}{12 f_r \sqrt{\varepsilon_{eff}}} \tag{14}$$

As with any other electrically small antenna, practical design of PIFA needs to have some finite ground plane. For optimum design of small patch antenna, it is required that the ground plane should be greater than the patch dimensions by approximately six times the substrate thickness (h) all around the fringe. Hence, the ground plane dimensions is given as (Rajat et al., 2013)

$$L_{gp} = 6h + l \tag{15}$$

$$W_{gp} = 6h + w \tag{16}$$

Where l and w are the patch length and width respectively.

The fundamental step taken in designing a new PIFA is to calculate the patch dimensions that will make the antenna resonate at the right frequency. The value of each of the parameters is calculated thus:
Width of patch for PIFA (L_2) is calculated using equation (14)

For PIFA at 900 MHz,
Substituting the values of $c = 3 \times 10^8 m/s$, $\varepsilon_r = 4.4$ (for FR4 substrate with permittivity of 4.4) and $f = 9 \times 10^8 MHz$ into equation 14 yields

$$L_2 = \frac{3\times10^8}{12\times9\times10^8\sqrt{\frac{4.4+1}{2}}} = 1.69 \times 10^{-2} m = 17mm$$

$$L_1 = 2L_2 = 2 \times 17 = 34mm$$

Since low profile antenna is needed, height of patch H is chosen to be equal to 2mm

H = W (Width of the short plate)

$\therefore \mathrm{H} = \mathrm{W} = 2\mathrm{mm}$

Length L_g and W_g of ground plane are derived from equation (15) and (16) respectively for

$h = 2$

$L_g = (6 \times 2) + 34 = 46\mathrm{mm}$

$W_g = (6 \times 2) + 17 = 29\mathrm{mm}$

The shorting plate is positioned at the corner of the planer element (width of patch) for maximum reduction in antenna size.

Calculations of Performance Limits [Bandwidth (BW), Gain (G) and Efficienc**y (η)]**

For all electrically small antennas, the impedance bandwidth (BW) is related to the quality factor (Q) and maximum allowable voltage standing wave ratio (S). For good performance, VSWR (S) should be less than or equal to 2 (i.e. $S \leq 2$) (Saisset and Travers, 2009). For this design, VSWR (S) = 2 is chosen. For perfect lossless material, the quality factor (Q) is given as

$$Q = \frac{1}{(ka)^3} + \frac{1}{ka} \qquad (17)$$

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$$

where k is the wave number, a is the radius of imaginary plane enclosing the antenna and c is the speed of light (Bancroft, 2003).

The entire ground plane of an electrically small antenna is included in the size of the antenna. Therefore, a is equal to half the length of the ground plane (L_g) i.e. $a = \frac{L_g}{2}$.

For $f = 900Mhz,\ k = \frac{2\pi \times 9 \times 10^8}{3 \times 10^8} = 6\pi$

Impedance bandwidth (BW) is obtained using equation (18) given as

$$BW = \frac{S-1}{Q\sqrt{S}} \qquad (18)$$

where S and Q are the voltage standing wave ratio and quality factor of the antenna respectively (Bancroft, 2003).

Upper limit of Gain (G) and efficiency (η) are calculated using equations (19) and (20) respectively which are (Skirvervik et al, 2001)

$$G = (ka)^2 + 2ka \qquad (19)$$

$$\eta = \frac{1}{1 + Q\tan\delta} \qquad (20)$$

Performance Limits for PIFA with FR4 substrate are calculated as follows

At $f_0 = 900MHz,\ L_g = 50mm,\ a = 25mm,\ k = 6\pi,\ \delta = 0.02$

From equation (17), quality factor Q is

$$\therefore Q = \frac{1}{(6\pi \times 0.025)^3} + \frac{1}{6\pi \times 0.025} = 11.674$$

This implies that from equation (18), the impedance bandwidth is

$$BW = \frac{2-1}{11.674\sqrt{2}} = 0.061 = 6.1\%$$

The gain G and radiation efficiency η are obtained from equations (19) and (20) respectively as

$$G = (6\pi \times 0.025)^2 + 2 \times 6\pi \times 0.025) = 1.17dB$$

$$\eta = \frac{1}{1 + 11.674\tan(0.02)} = 0.9959 = 99.6\% \quad (where\ \delta = 0.02\ for\ FR4\ substrate)$$

Result and Discussion

High frequency Structural Simulator (HFSS), computational electromagnetic based commercial software, was used to simulate the designed antenna and the result is as shown below.

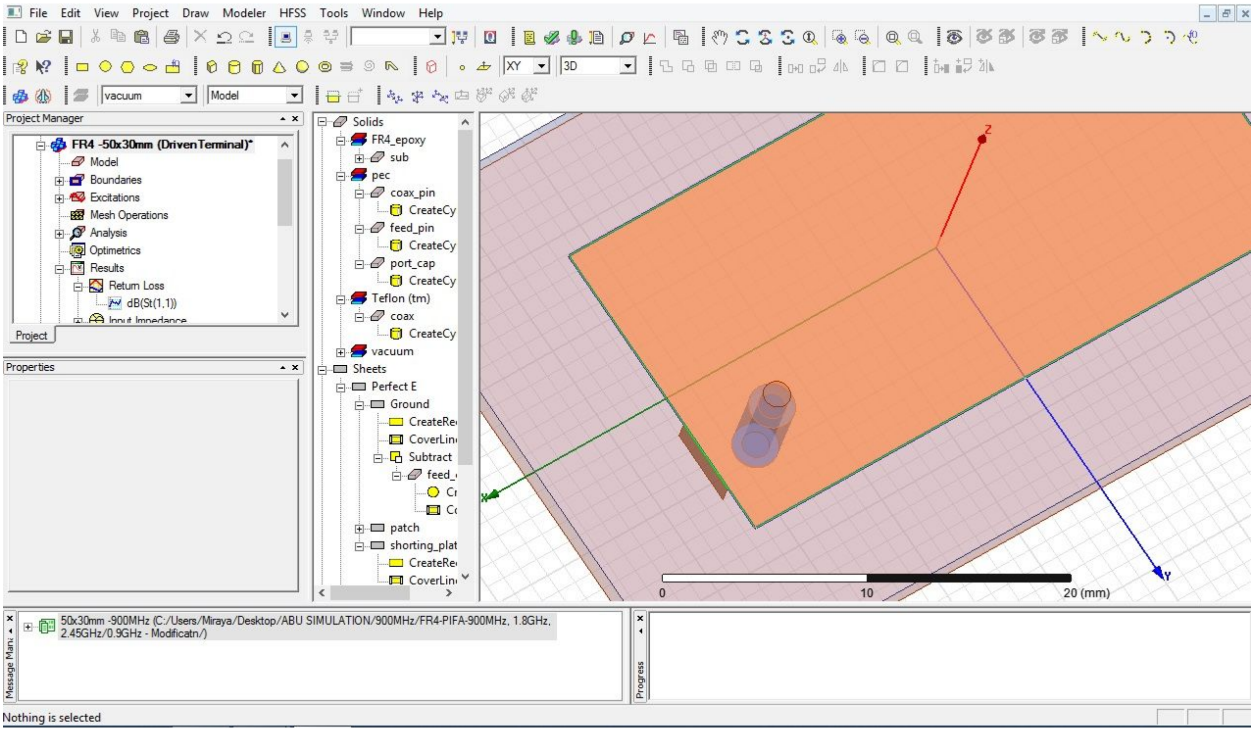

Fig. 2: Simulated structure of PIFA

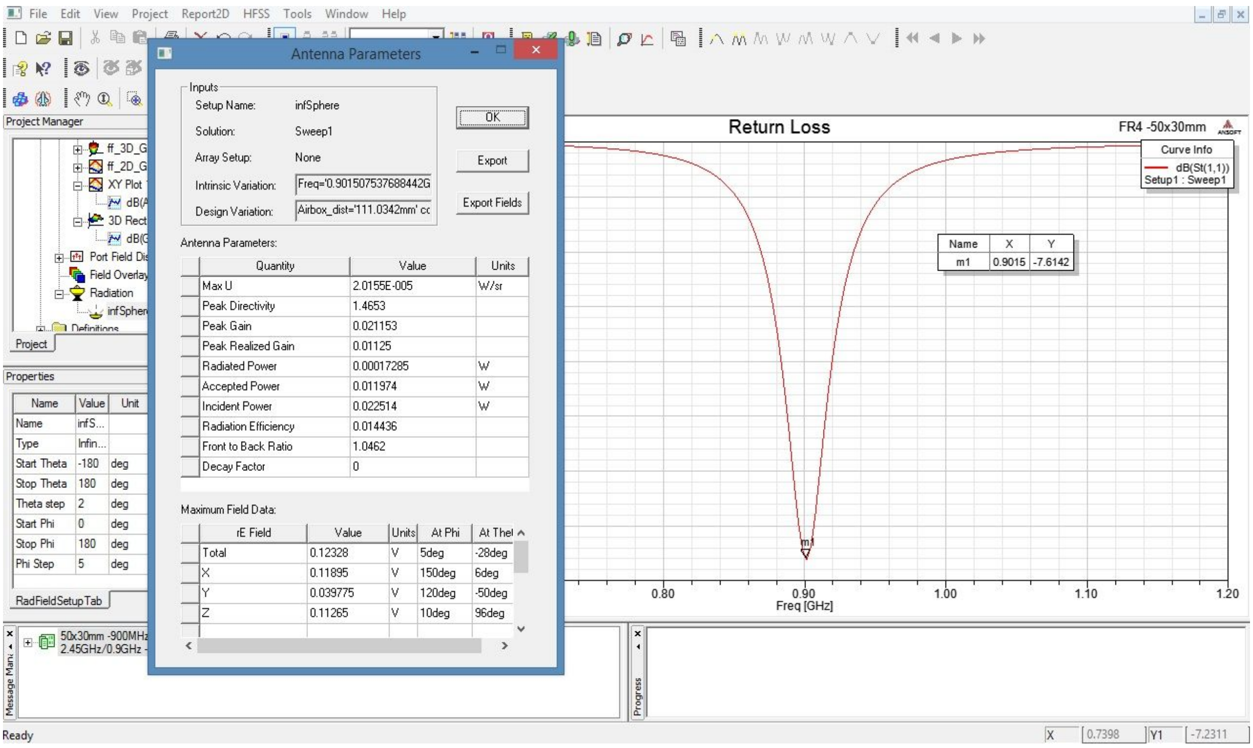

Fig. 3: Simulated Antenna Performance Parameters

Figures 2 and 3 show the structure and parameters of simulated PIFA respectively. The results read from figure 3 are clearly presented in table 2. The dimensions of the antenna radiator (patch) are 34mm by 17mm while the entire antenna dimension is 50mm x 30mm x

2mm making the designed antenna small enough to be embedded inside the body. Table 2 reveals that the resonance frequency of the designed antenna is within the desired range of ISM 900MHz band i.e. 902 – 928MHz. The return loss of $-7.61dB$ obtained implies that the reflection loss of the antenna is less than 25%.

On the other hand, the results of calculated values of bandwidth, efficiency and gain based on theory of fundamental limit of electrically small antennas and stimulated ones (table 3) show that the designed antenna has good impedance bandwidth and gain but low radiation efficiency. The calculated gain, radiation efficiency and impedance bandwidth of the antenna give the upper limits required for effective small antenna performance and as antennas become smaller, the limits on bandwidth and efficiency become difficult to attain because of their direct relationship with the size of the antenna.

Table 2: Designed parameters and simulated results of PIFA at 900MHz

Parameters (mm)							Results					
L_g	W_g	L_1	L_2	H	W	D_s	F_R (MHz)	S_{11} (dB)	BW (MHz)	G (dB)	H	E (dB)
50	30	34	17	2	2	5	902	- 7.61	20	1.41	1.44	0.12

Table 3: Calculated and Simulated Values of three main performance characteristics of PIFA (Bandwidth (BW), gain (G) and radiation **efficiency (η))**

Antenna	F_r (MHz)	Calculated values			Simulated values		
		BW (%)	Gain(dB)	η (%)	BW (%)	Gain(dB)	η (%)
PIFA	900	6.1	1.17	99.6	2.22	1.41	1.44

Low bandwidth and radiation efficiency recorded may be due to the small ground plane size and height of the substrate. Increase in substrate height results in the introduction of surface waves which extract power from the total available power for direct radiation. Moreover, this does not encourage miniaturization which is a critical factor in the application under consideration. More so, thick substrate with low permittivity have been known to provide better efficiency and larger bandwidth but provides loose bound fields for radiation into space. Again the application of interest are used within the human body, hence there is need to minimize undesirable radiation. The SAR of the antenna is very good as indicated by the value of the electric field which is 0.12dB.

Conclusion

Planer Inverted – F Antenna was designed based on transmission line model. The designed antenna was simulated with computational electromagnetic based commercial software known as High Frequency Structural Simulator. The simulated results show that the designed antenna has good return loss ($-7.61dB$), impedance bandwidth (2.22%), electric field (0.12dB) and gain (1.41dB) however, the radiation efficiency is low (1.44%). The size of the antenna is smaller than most conventional PIFA at the same frequency and cost. Hence, the designed PIFA is a good candidate for implantable medical devices. Nevertheless, the paper recommends that more effective miniaturization technique be employed in the design to improve the radiation efficiency, without making the antenna large and complex.

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