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Compact Stacked Planar Inverted-F Antenna for Passive Deep Brain Stimulation Implants

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***Abstract*— A compact meandered three-layer stacked circular planar inverted-F antenna is designed and simulated at the UHF band (902.75 - 927.25 MHz) for passive deep brain stimulation implants. The UHF band is used because it offers small antenna size, and high data rate. The top and middle radiating layers are meandered, and low cost substrate and superstrate materials are used to limit the radius and height of the antenna to 5 mm and 1.64 mm, respectively. A dielectric substrate of FR-4 of $\varepsilon_r = 4.7$ and $\delta = 0.018$, and a biocompatible superstrate of silicone of $\varepsilon_r = 3.7$ and $\delta = 0.003$ with thickness of 0.2 mm are used in the design. The resonance frequency of the proposed antenna is 918 MHz with a bandwidth of 24 MHz at return loss of -10 dB in free space. The antenna parameter such as 3D gain pattern of the designed antenna within a skin-tissue model is evaluated by using the finite element method. The compactness, wide bandwidth, round shape, and stable characteristics in skin make this antenna suitable for DBS. The feasibility of the wireless power transmission to the implant in the human head is also examined.**

I. Introduction

Deep brain stimulation (DBS) is an effective medical treatment for a wide range of neurological and psychiatric disorders such as Parkinson's disease, Alzheimer's disease, dystonia, treatment resistant obsessive compulsive disorder, depression, essential tremor, epilepsy, etc. It is a two steps procedure: (i) first, electrodes and leads are implanted in the brain, and (ii) next, an implantable pulse generator (IPG) is positioned in lateral chest wall, anterior abdomen, etc.

The IPG delivers electrical pulses to electrodes through long insulated wires. To generate an electrical pulse train, a battery is embedded in the IPG. The battery needs to be replaced in few-year intervals whenever it is discharged. In addition, generally the IPG is implanted in the chest or abdomen and extension wires go through the skin passing behind the ear connecting the IPG and the electrodes. This long extension wire may cause infection and erosion, lead fractures and connector problems [1-3]. Thus, the DBS demands new stimulators which are smaller, implanted subcutaneously on the cranium itself. The difficulties associated with the battery and the extension wires can be also tackled by passive batteryless stimulation implants [2].

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Powering passive implanted medical implants will require transcutaneous energy transfer or harvesting energy from the human body. Although attempts are being made to use the seebeck thermoelectric effect, vibrations or body movements to harvests power from the body, no functional solution is currently available. Glucose fuel cells are also another promising candidate as they produce electrical energy from physiological fluids. But the generated power is very low to operate existing DBS implant [4]. To satisfy the power requirement of the existing implanted technology, two other types of power transmission techniques including inductive coupling and far field coupling can be considered. These techniques can provide sufficient energy to the DBS implant from outside the brain whenever needed. In a short range communication between an external source of energy and a passive implant, inductive coupling can be used for powering the implant. The inductive coupling refers to the transfer of energy from an external circuit to the implant by virtue of the mutual inductance. On the other hand, the far field coupling uses electromagnetic waves emitted from the source of energy in a far field region to power the passive implant. In this work, the objective is to power a passive DBS implant wirelessly through the electromagnetic energy of the incoming waves emitted by a transmitter. In this approach, an on-chip antenna is required in the passive implant to collect the transmitted electromagnetic waves. Accordingly, a proper antenna is designed and modeled to be used on-board of a passive DBS implant as the key component for extracting energy through a far field energy transmission mechanism [5, 6].

In recent years, the communication band known as the medical implanted communication service (MICS) band is being considered for medical applications such as DBS, implanted biotelemetry, peacemakers, drug delivery, and so on. The MICS frequency band (402 - 405 MHz) is a good choice for achieving low levels of attenuation, as the attenuation of the EM energy in human body increases with the increase of frequency. But the MICS frequency band has drawbacks such as large antenna size, and low data rate. On the other hand, the ultra-high frequency (UHF) band (860 – 960 MHz) is a better candidate for DBS applications because of the smaller antenna size, and higher data rate [7, 8].

In this paper, first, a compact implantable stacked circular PIFA is proposed for DBS applications. Then, antenna parameters such as return loss (S_{11}), and 3D gain pattern are simulated in free space using electromagnetic modeling software employing the finite element method

(FEM). Next, the antenna parameters are investigated in a skin tissue model. Finally, the feasibility of power transmission to the implant from an external transmitter is analyzed.

II. ANTENNA DESIGN

A planar inverted-F antenna (PIFA) contains a ground plane, a radiating element, a feed wire and a shorting pin which connects the radiating element to the ground plane. It belongs to the group of unbalanced antennas because it gives a low profile modification of the quarter wave monopole. The shorting pin works as a return path for the facial current of the antenna. It triggers resonance for electrical dimensions smaller than $\lambda/2$. Therefore, the PIFA is a suitable antenna for systems where the space volume for the antenna is limited since its regular size is in the order of $\lambda/4$ [9, 10]. The empirical equation of resonant frequency of PIFA is as follows:

$$f_o \cong \frac{c}{4\,(L+W)} \tag{1}$$

where c is the speed of light in free space, L and W are the length and width of the radiating plate. However, the equation provides only a rough estimate of the resonant frequency and does not involve all the parameters which significantly influence the resonant frequency of the PIFA. Therefore, a more comprehensive design equation is required to guide the design for practical applications [11]. Accordingly, the resonant frequency of the PIFA which includes some other significant parameters is thus given by:

$$f_o \cong \frac{c}{4\sqrt{\varepsilon_{eff}}\,(l_1 + l_2 - w + h)}\ . \tag{2}$$

where c is the speed of light in free space, w is the width of the short, h is the thickness of the substrate, l_1 and l_2 are the dimensions of the radiating patch, and ε_{eff} is the effective permittivity of the substrate material between the radiating patch and the ground plane. The effective permittivity ε_{eff} is approximated as [12, 13]:

$$\varepsilon_{eff} \cong \frac{\varepsilon + 1}{2}\,. \tag{3}$$

Fig. 1 shows the configuration of the proposed three-layers stacked circular PIFA whose volume is $\pi \times 5^2 \times 1.64$ mm^3. Among the three circular layers, the bottom layer works as ground plane and the other two vertically stacked circular layers serve as radiating patches. The radius of the ground layer and the first and the second radiation layer are 5 mm. Each of the radiating patches are printed on an 0.7466 mm thick dielectric substrate FR-4 of $\varepsilon_r = 4.7$ and $\delta = 0.018$. The microstrip design approach is used due to the flexibility in design, conformability and shape while the stack and the meandering techniques are applied to increase the length of current flow path and cut down the physical size of the antenna [14]. The round structure of the proposed antenna makes it easy for use in DBS implants. A 0.2mm thick silicone superstrate covers the total antenna to preserve their biocompatibility and robustness. The superstrate can protect neighboring tissues surrounding the implanted antenna against the heat from the antenna radiation. It acts as a buffer between the antenna and human tissues by reducing RF power at the locations of lossy human tissues. It also helps the antenna to be well matched to the 50 Ω feed line through decreasing effects of the high conductive biological tissues [15].

In order to simulate the antenna, a 50 Ω coaxial probe with radius of 0.4 mm is used to feed the first radiating patch. A conductor of 0.4 mm radius is used to connect the first radiator to the second radiator. A shorting pin, which minimizes the resonance length of the PIFA of 0.2 mm radius, connects the ground plane to the lower patch [16]. As a requirement of the simulation software, free space surrounds the antenna by 90 mm ($\lambda_0/4 \approx 82$ mm, where λ_0 is the free space wavelength at 918 MHz) in the top and the bottom side of the antenna. The proposed design achieves significant miniaturization compared to the previously reported implantable PIFA antennas operating in the UHF band, while emphasis is given to the biocompatibility and availability of the materials [17, 18].Three meanders are used in each radiator. The width of each meander is 1.0 mm. The upper patch is a reversed version of the lower patch. The origin of the coordinate system is assumed to be at the center of the PIFAs' ground layer.

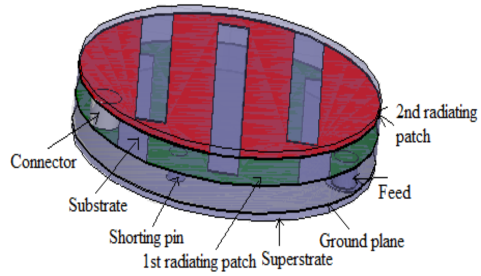

Figure 1. Configuration of the proposed stacked PIFA antenna.

III. ANTENNA PERFORMANCE

The optimal antenna parameters are obtained by an iterative simulation test using a FEM based simulation software. Fig. 2 shows the frequency response of the return loss (S_{11}) of the proposed PIFA. The resonant frequency of the designed PIFA is 918 MHz which is in the frequency range of the UHF band (902.75 - 927.25 MHz). The input impedance of the proposed antenna is attained as $Z_i = 44.028 + 0.0398j$ at 916 MHz as shown in Fig. 3. It can be observed from Fig. 3 that the antenna has zero reactance at around 916 MHz, and in other frequencies of the specified band it is inductive. The bandwidth of 24 MHz (906 – 930 MHz) at a return loss of -10dB in the UHF band is obtained. Fig. 4 represents the 3D far field gain pattern of the proposed antenna. As the antenna is electrically very small, nearly omnidirectional radiation is realized. Maximum gain value of -29 dB is recorded. In order to assess the performances of our designed antenna, we can compare the antenna parameters with those of previously reported antennas. For instance, the maximum gain of our designed antenna of -29 dB is much higher than the maximum gain of -55.65 dB for a miniaturized implantable PIFA designed by Kiourti et al. [19]. The bandwidth of the designed PIFA of value of 24 MHZ is much broader than that of 8 MHz for an UHF PIFA reported by Louhichi et al. [17]. The simulated radiation efficiency of the proposed PIFA is found to be 34.34% at 918 MHz which is higher than the radiation efficiency of 18% presented by Hae-won et al. (2008) for their RFID PIFA antenna [20].

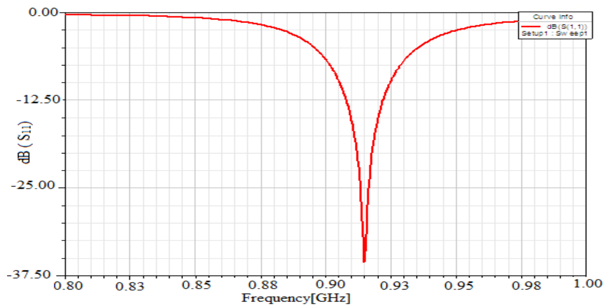

Figure 2. Simulated frequency response return loss (S_{11}).

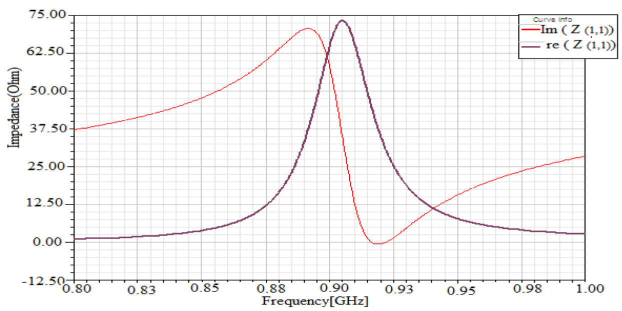

Figure 3. Impedance characteristic of the PIFA antenna.

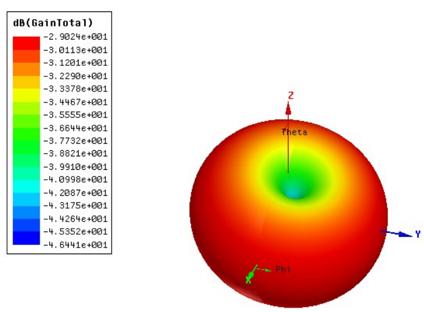

Figure 4. 3D far field gain pattern of the proposed antenna.

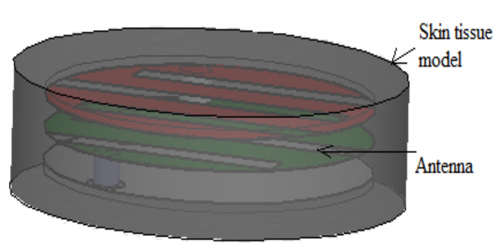

Figure 5. Antenna implanted in skin tissue model of human head.

Since the proposed antenna is desired to be implanted into human head, the antenna is next analyzed by implanting it into the skin-tissue layer, which has a permittivity of 40, conductivity of 0.8 S/m, and mass density of 1080 kg/m^3 when operating at 918 MHz [21]. A cylindrical skin-tissue model as indicated in Fig. 5 of 5.5 mm radius, and 3 mm height is used in this simulation, thus 0.5 mm skin layer is on top and bottom side of the antenna. The 3D gain pattern obtained in skin-tissue model is quite similar with the gain pattern in free space. The maximum gain of the antenna inside the skin is -35.32 dB which is less than the gain of –29 dB attained in free space due to dielectric loss property of skin. The return loss is increased inside skin tissue model due to the loading effect of the skin tissue. The implantation of the antenna under the skull is not feasible due to dielectric loss properties of different layers of the head and space limitation. The antenna implantation under the skin is preferable because of unstable and weak communication link with antenna inside the skull.

IV. Characterization of the Communication Link

We have assumed that the proposed antenna is implanted under the skin of the head for DBS applications. The antenna will receive signals from an external transmitter. The received signal will contain not only data but also energy for the passive implant. The DBS implant also requires a communication link with an external control unit that could determine and relay the desired stimulation parameters to the implant. In order to characterize the performance of this link, the setup of Fig. 6 is considered. In this setup, the proposed antenna is implanted in skin tissue model of the head, and is considered as a receiver antenna. The external antenna works as transmitter antenna which is placed above the skin tissue model. A communication link will be established between the two antennas [16].

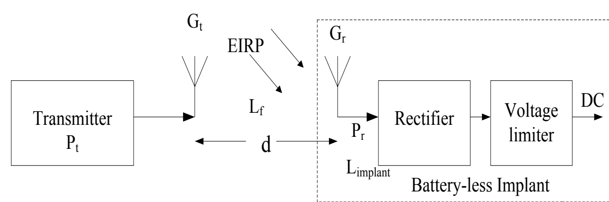

Figure 6. Wireless power transmission in the UHF passive system.

To find out the link budget, it is necessary to know some parameters related to link. The key parameters are as follows: the operating frequency is fixed to 918 MHz, the output power of the external transmitter antenna is 1 W, the distance between transmitter antenna and implant is assumed as 0.5 M. The transmitter antenna is considered to be a microstrip antenna. Table I represents the parameters involved in the calculation, and the values of the parameters and the power received by the implant.

The modified version of the Friis transmission equation that describes the amount of power received by the implant inside the skin of the human head (assuming the antennas have an impedance and polarization match) is as follows:

$$P_r(dB) = P_t + G_t - L_{tfeed} - L_f - L_a + G_r - L_{rfeed} - L_{implant} \quad (4)$$

$$L_f = 10\log_{10}(4\pi d/\lambda)^2 [dB] \quad (5)$$

where, P_r (dB) is the power received by the implant, G_t (dB) is the gain of the transmitter antenna, L_{tfeed} is the transmitter feeding loss, L_a is the air propagation loss, G_r is the implant antenna gain in free space, L_{rfeed} is the receiver feeding loss,

L_f is the free space loss which is given by (5), and $L_{implant}$ (dB) is the loss due to dielectric properties of skin tissue [22].

The antenna receives power of 3.17 mW, and power harvesting circuit provides output of 2.916 mW. This power is sufficient for the operation of a compact low power implant. If the implant system needed more power, then either transmission power should be increased or the link distance should be reduced but the maximum SAR value inside the human head must remain below the regulated limitation of ANSI.

TABLE I. CALCULATED PARAMETERS OF LINK BUDGET

Transmitter	
Frequency	918 MHz
Transmitted power (P_t)	30 dBm
Transmitter feeding loss (L_{tfeed})	0 dB
Transmitter antenna gain (G_t)	6 dBi
EIRP (P_t+G_t- L_{tfeed})	36 dBm / 6 dBW
Receiver	
Receiver antenna gain (G_r)	-29 dB
Receiver feeding loss (L_{rfeed})	0 dB
Loss due to skin tissue, ($L_{implant}$) [23]	6.32 dB
Propagation	
Distance (d)	0.5 M
Free space loss (L_f)	25.67 dB
Air propagation loss (L_a)	0 dB
Calculated received power	
Power received by implant (P_r)	-24.99 dB (3.17 mW)
DC power output (assume 92% efficiency)	2.916 mW

V. CONCLUSION

An implantable three-layer stacked circular PIFA for DBS applications was designed and simulated at the UHF band. It is confirmed that this antenna is suitable for use in implants in the human head because of its compact volume of $\pi \times 5^2 \times 1.64$ mm^3, circular structure, and wide bandwidth of 24 MHz. The peak gain of the antenna was -29 dB at 918 MHz in free space. According to link budget, the proposed implanted antenna received 3.17 mW from a transmitter which was 0.5 M away radiating 1 W power. This link budget confirmed that wireless power transfer to passive implants and bidirectional communication is possible. Therefore, this antenna is suitable for wireless DBS application. According to the results, the use of the simplified skin tissue model is likely to be valid, but further investigation is required to validate it in a complex human head model. In our future work, fabrication and experimental validation will be carried out to establish wireless connectivity between the implant and an off-body transceiver.

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