Simulation of Implantable Miniaturized Antenna for Brain Machine Interface Applications

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Abstract ─ Due to the limited size of antenna and electromagnetic loss of human head tissue, implantable miniaturized antennas suffer low radiation efficiency. This work presents simulation and analysis of implantable antennas for a wireless RF-powered brain machine interface applications. The accuracy and stability of antenna input impedance simulation are presented. The effects of the implanted antenna's insulating layers and position within the human brain on the antenna's input impedance, frequency bandwidth, and power transmit are studied. The results show that thin (on the order of 100 micrometers thickness) insulating layer can significantly impact the antenna performance. Proper selection of electrical properties of insulating layers and position inside human head tissues can facilitate efficient RF power reception. While the results show that the effects of the human head shape on antenna performance is somewhat negligible, the electric properties of the tissues surrounding the implanted antenna can significantly impact the electrical characteristics (efficiency, input impedance, and operational frequency) of the implanted antenna.

Keywords- FDTD, transmission line model, antenna insulating layer, implantable antenna, Brain Machine Interface, input impedance, human head model, wireless power transmission

1. INTRODUCTION

Brain Machine Interface (BMI) establishes a communication channel between a human brain and outside analyzing stations or neuroprosthetic devices which facilitate the treatment of neural dysfunction. However, because of the limitation of the power supply, most current BMIs have only been designed for immobile users in a carefully controlled environment.

Battery is one of the widespread BMI power supply units [1] [2]. However it presents a lot of problems due to the size, mass, potentially toxic composition, and finite lifetime. As such, there have been several research groups using inductive coupling method to transfer the power wirelessly [3]. The coupling coils have been typically working at 10MHz or below (quasi-static field). Its drawback is coils' transmission mainly depends on the changing of magnetic field flux and therefore acceptable coupling will depend on the dimensions of the receive coil which leads to occupying a relatively large area to implant inside the human tissue. The other problem is the distance between two coupling coils will be limited to a small value to maintain the good coupling. Moreover, there will be potential dermonecrotic problems caused when two coupling coils are very near each other and skin is in between. These obstacles demonstrate the need for a safe way to transmit the power to the implanted chip wirelessly. Implanted antenna module could be designed into a very small profile providing a promising approach to solve the safety problem and realize a long term implantation of BMI in users.

The design of an implantable antenna inside the human body is extremely challenging. The human environment limits the size of the antenna and at the same time there are very strong conductive losses in human body [4]. Therefore antennas' transmission/reception efficiency can be highly compromised. Most implantable antennas have been analyzed are studied at the medical implant communication service (MICS) band of 402-405 MHz. For GHz and above operating frequencies, the impact of the thin coating thickness changed with time at 2.4GHz for an implanted antenna radiation measurement setup [5]. A pair of microstrip antennas working at microwave frequencies (1.45 and 2.45 GHz) established a data telemetry link for a dual-unit retinal prosthesis in [6]. All these referenced papers are assuming that the implanted antennas are connected with 50 Ohm transmission line.

It is noted however, that the ratio between received RF power and tissue absorption depends on the input impedance of the receive antenna, operating frequency and distance between transmit and receive antennas [7]. To realize the conjugate matching (i.e. optimal performance), evaluation of the antenna input impedance is crucial for BMI chip design. In this work, we characterize the input impedance of the BMI RF power receiving antenna working at a radio frequency (RF) above 1GHz. The antenna loads which include connected wires and implanted chip could be designed to other values rather than being restricted to 50Ohms. Furthermore, the efficiency of wireless implants is related to 1) body size, 2) implanted antenna design including dimensions, geometry, and thickness of insulating layers, 3) location of implants, and 4) tissue compositions [8]. As a result, we evaluate the impact of these issues on a wireless implanted BMI system.

2. SIMULATION METHODS AND HUMAN MODEL

The input impedance of classic antenna structure could be calculated analytically when the antenna is placed in the free space, buried in materials, or even embedded inside one lossy material. However, it is extremely challenging to analytically calculate the impedance of insulated antennas with arbitrary structures embedded in human body, requiring the use of full wave CEM.

FDTD method has great advantage for interactions of EM waves with biological tissues [9]. For example in [9], the aim was to simulate antennas' input impedance in order to calculate RF power transmitted under specific absorption rate (SAR) regulation. The input impedance and the received power were calculated through voltage and current information in a transmission line model implemented with FDTD algorithm.

In our work, a one dimensional transmission line feed model is implemented with the standard three dimensional FDTD algorithms [10]. Transmission line model's current contour is shifted one cell from gap to reduce fringing field in the gap [10]. One cell gap feeding models converge to the true value if using fine grids [11]. So sub-mm spatial resolution is used in this work. Around 2.4 GHz (frequency of interest), the minimum wavelength (15mm) shows up in high water content material such as Cerebra Spinal Fluid in human head tissues. Sub-mm (0.3mm and 0.165mm) spatial resolution was used to satisfy numerical dispersion. FDTD spatial resolution and time step were calculated to satisfy the stability criterion.

To analyze the thin insulating layers effects on the antennas performance, thin material sheet is modeled using a sub-cell modeling formula in FDTD [12]. This efficient sub-cell modeling method removes the limitation of spatial information must larger than the cell grid and therefore greatly reduce the storage requirement and computational time. Antennas were implanted inside a 19 materials head model which is developed from 1.5 Tesla MRI images [13].

3. RESULTS AND DISCUSSIONS

A. The accuracy of simulations

A dipole antenna was simulated in free space. The simulation results of dipole antenna in air are comparable with the measurement results [14] shown in Figure 1. The agreement between the simulation and the measurement results from 0.5GHz to 4.5GHz verifies the validation of the FDTD and transmission line simulation models.

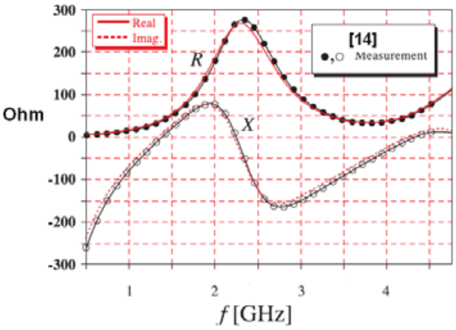

Fig 1: Input impedance of a dipole antenna: simulations vs. experiments.

B. Effects of Thickness of thin insulating layer on the input impedance of implanted antenna

The effects of insulation layers were discussed in [15]. It was shown that insulation coating affects antenna transmission efficiency. Micrometer scale insulating layers thickness impacts were tested in this work. In our simulations, a 3mm by 12mm rectangular antenna surrounded by insulating layers was numerically implanted inside the 19 materials head model. The thicknesses of insulating layers were changing from 25um to 200um. The relative dielectric constant of the insulating layers was 2.1. Simulation results are shown in Figure 2.

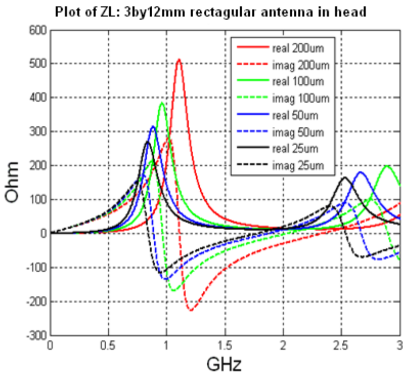

Fig 2: Effects of thin insulating layers on antenna input impedance. The antenna is implanted inside a 19-tissue anatomically-detailed human head model.

The results in Figure 2 demonstrate that the thickness of insulating layers significantly impacts antenna’s resonance frequency and radiation impedance, which in turn affects antenna’s radiation efficiency. When antenna is implanted inside the human head model, the dielectric constant of insulating is much smaller than that of the head tissues. The velocity of light will be higher in the small dielectric constant material thus yielding longer operating wavelength. Therefore the resonant frequency of the same length antenna will shift to higher frequency when compared to non-insulating cases. This effect increases with insulating layer becoming thicker. The radiation impedance also increases because of the decreased average dielectric constant in the antenna surrounding volume. In other words, the lossy material is moved away from the near field of the implanted leading to higher radiation efficiency. For example, the 200um insulating layer antenna’s radiation resistance doubles that obtained with the 25um insulating layer antenna (Figure 2).

C. Effects of the dielectric properties of tissues on input impedance of implanted antennas

Simulation results (in Figure 3) show that not only the thickness of the insulating material affects antenna performance, but also the dielectric properties of tissue. Antenna resonant frequency shifts to lower frequency when antenna embedded inside a high dielectric constant insulating layer. Figure 3 shows that the first resonant frequency is at about 1.5GHz when the dielectric constant is 3.4 (F/m). If antenna embedded in dielectric constant equals to 34 (F/m), the center resonant frequency shifts to about 0.8 GHz. The higher averaged dielectric constant however reduces the radiation impedance of the antenna which in turn will reduce the radiation efficiency. Therefore there is a tradeoff between high radiation efficiency and small antenna dimension.

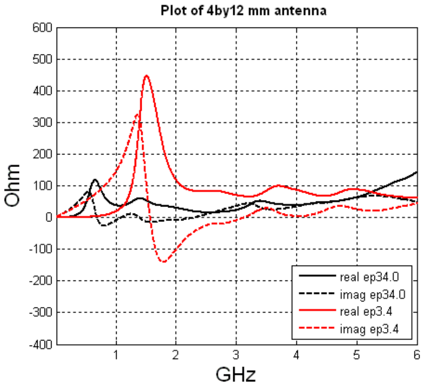

Fig 3: Effects of antenna insulating material on performance of implanted antenna

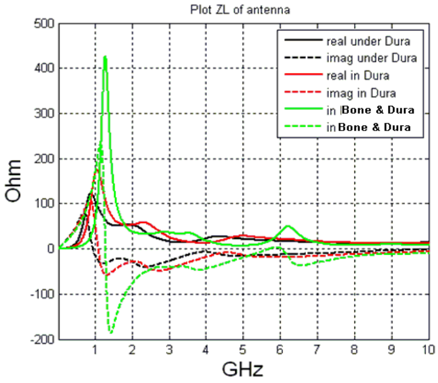

Fig 4: Effects of surrounding tissue properties on performance of the implanted antenna

Figure 4 displays antenna input impedance at different implanted positions inside the human brain. The results show that the implanted antenna performs very differently in bone and in Dura while the same Antenna performs comparably when the antenna is implanted in Dura and directly under Dura. This is because under Dura, the tissues are combination of grey matter and Dura and the average tissue property is similar to that of the Dura itself.

D. phantom and head model load

To answer whether head phantom shape and properties will change antenna performance, this section discuses antenna performances in a multi tissues head model, in a homogeneous head model and a head-sized rectangular phantom model as shown in Figure 5.

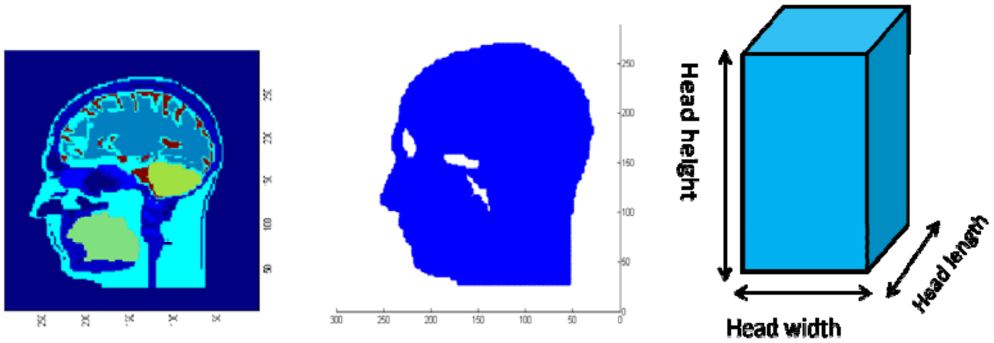

Fig 5 Multi-tissue head model, homogenous head model and head-sized homogenous rectangular phantom model

To test the model phantom shape affects, the first tested case is a 3mm by 12mm rectangular antenna with 1mm insulating layer implanted at 19 mm depth inside the human head (under Dura.). The same insulated antenna was implanted in the same position in the homogenous head phantom and in the homogenous rectangular phantom. The homogenous phantoms both have property of dielectric constant equals 48.201, conductivity equals to 0.99 which represent the average dielectric properties of Dura and grey matter. Figure 6 shows that the input impedances of antennas antenna are similar for all three cases, concluding that phantom shape does not impact antenna impedance.

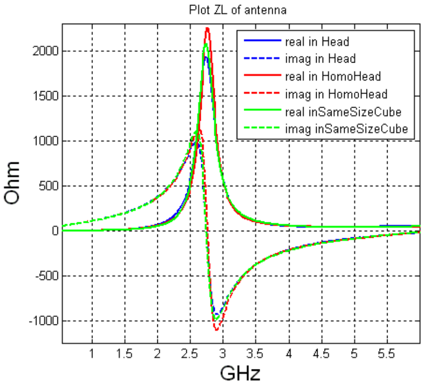

Fig 6 Impedance of antennas implanted inside different head models shown in Fig 5.

4. CONCLUSIONS

The results show that micrometer thickness insulating layer can significantly impact implanted antenna performance. Proper selection of electric properties of insulating layers and position inside head tissues would facilitate RF power transmission. Head model shape is not a critical factor while dielectric properties of surrounding tissues can impact the implanted antenna input impedance.

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