IMPLANTABLE ANTENNAS FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

Biomedical telemetry permits the measurement of physiological signals at a distance, through either wired or wireless communication technologies. Physiological signals are obtained by means of appropriate transducers, post-processed, and eventually transmitted to exterior monitoring/control equipment. One of the latest developments of bio medical telemetry is in the field of implantable medical devices (IMDs). Low-frequency inductive links have long been the most prevalent method of biotelemetry for implantable medical devices. However, they suffer from low data rates (1-30 kbps), restricted range of communication (< 10 cm), and increased sensitivity to inter-coil positioning. To overcome these limitations, research is currently oriented towards radiofrequency (RF)-linked implantable medical devices.

I. INTRODUCTION

Millions of people worldwide depend upon implantable medical devices to support and improve the quality of their lives. RF-linked implantable medical devices are already in use for a wide variety of applications, including temperature monitors, pacemakers and cardioverter defibrillators, functional electrical stimulators (FES), blood-glucose sensors, and cochlear and retinal implants. As technology continues to evolve, new implantable medical devices are being developed, and their use is expected to rapidly increase from an already large base.

Until recently, no globally accepted frequency band had been dedicated to biotelemetry for implantable medical devices. The situation changed with the ITU-R Recommendation SA.1346, which outlined the use of the 402.0-405.0 MHz frequency band for Medical Implant Communications Systems (MICS). The MICS band is currently regulated by the United States Federal Communications Commission (FCC) and the European Radio-communications Committee (ERC). The 433.1-434.8 MHz, 868-868.6 MHz, 902.8-928 MHz, and 2400-2500 MHz Industrial, Scientific, and Medical (ISM) bands are also suggested for implantable medical device bio telemetry in some countries [2].

However, focus is on the MICS band, because of its advantages of being available worldwide and being feasible with low-power and low-cost circuits, reliably supporting high-data-rate transmissions, falling within a relatively low-noise portion of the spectrum, lending itself to small antenna designs, and acceptably propagating through human tissue. A key and critical component of RF-linked implantable medical devices is the integrated implantable antenna, which enables bidirectional communication with the exterior monitoring/ control equipment. Patch designs are currently receiving considerable attention for implantable antennas, because they are highly flexible in design, shape, and conformability, thus allowing for relatively easy miniaturization and integration into the shape of the implantable medical device. In a realistic scenario, implantable patch antennas will be mounted on the existing hardware of the implantable medical device, which will also serve as the ground plane.

The design of implantable patch antennas has attracted high scientific interest for fulfilling the requirements of biocompatibility, miniaturization, patient safety, and high-quality communication with exterior equipment. Numerical and experimental investigations are also highly intriguing.

II. IMPLANTABLE ANTENNA BIOCOMPATIBILTY

Implantable antennas must be biocompatible in order to preserve patient safety and prevent rejection of the implant. Furthermore, human tissues are conductive, and would short circuit the implantable antenna if they were allowed to be in direct contact with its metallization. Biocompatibility and prevention of undesirable short-circuits are especially crucial in the case of antennas that are intended for long-term implantation. The most widely used approach for preserving the biocompatibility of the antenna – while at the same time separating the metal radiator from human tissue – is to cover the structure with a superstrate dielectric layer as shown in Fig 1.1.

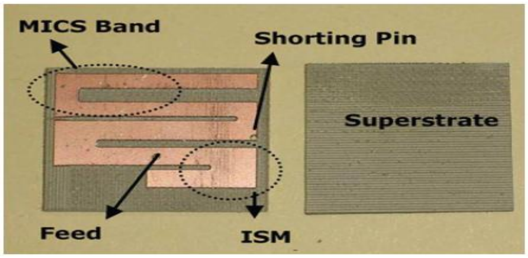

Fig1.1: Biocompatibility issues for implantable patch antennas: the addition of a superstrate.

Commonly used biocompatible materials include Teflon (permittivity, ε r = 2.1; dielectric loss tangent, tanδ = 0.001), MACOR® (ε r = 6.1; tanδ = 0.005), and ceramic alumina (ε r = 9.4; tanδ = 0.006) [3]. However, it is important to highlight that ceramic substrates do not easily lend themselves to drilling and round cuts.

III. IMPLANTABLE ANTENNA DESIGN STRATEGIES

Several strategies have been proposed for implantable antenna design. These are mainly dictated by the fact that antennas are intended to operate inside human tissue instead of free space. The antenna should therefore be designed inside free space, and further refined for tissue implantation, or designed directly inside an environment surrounded with human tissue.

Use of a single-layer tissue model is the simplest and fastest option when designing implantable antennas directly inside tissue material. Following this methodology, antennas are designed for a “generic” tissue-implantation scenario. Simplified tissue models in the shape of a cube, a rectangular parallelepiped and a cylinder have been used for this purpose. The design is performed by selecting the dielectric material, and subsequently optimizing all antenna design parameters to refine tuning at the desired operating frequency.

Another option is to design the antenna for a specific implantation site by taking into account a specific region of the body. A multilayer tissue model, with either finite or infinite dimensions, is selected in this case. For example, implantable antennas intended for trunk and chest implantation can be directly designed inside three-layer planar tissue models consisting of skin, fat, and muscle tissues.

Recently, a novel two-step design methodology has been proposed for implantable antennas. This emphasizes design speed-up and optimized resonance performance inside a specific implantation site. This involves an approximate antenna design inside a simplified tissue model (a cube filled with the intended tissue material), and further quasi-Newton optimization inside a canonical model of the desired implantation site. Despite being optimized inside a canonical tissue model, the designed antennas were shown to exhibit insignificant resonance discrepancies inside detailed anatomical tissue models [2].

IV. STUDY OF NUMERICAL PROCESS: TISSUE MODELS

In numerical simulations, implantable antennas are analyzed inside inhomogeneous lossy media that simulate biological tissues. Biological tissues have their own permittivity (ε r), conductivity (σ), and mass-density values.

Canonical Tissue Models are often used to speed up simulations, and to ease the design of implantable antennas. These may be a single layer, thus accounting for a generic tissue implantable antenna. They may also be multilayer, thus providing a simplified model of a specific implantation site inside the human body as shown in Fig.1.2.

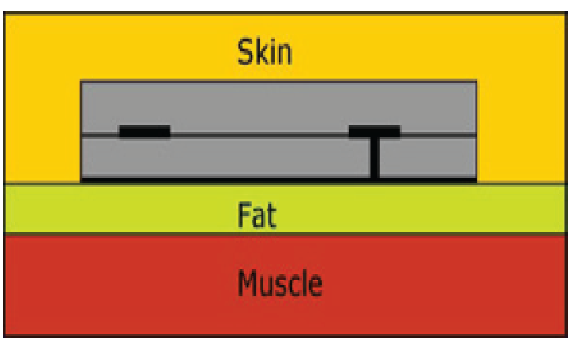

Fig 1.2: A three- layer (skin/fat/muscle) canonical tissue model

Anatomical Tissue Models are often used to obtain more realistic results. Anatomical tissue models are produced by the combination of magnetic-resonance imaging (MRI) or computer tomography (CT) data with the electrical properties of human body tissues as shown in Fig 1.3.

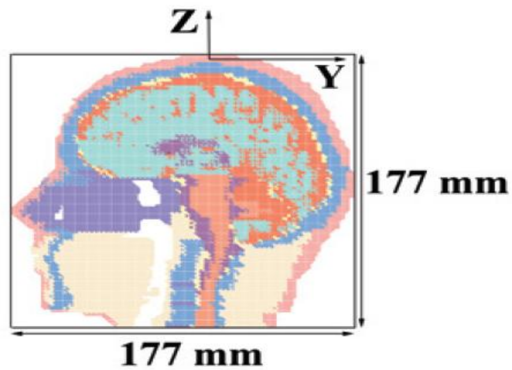

Fig 1.3: An anatomical human head tissue model

As far as antenna design is concerned, it is important to highlight that multilayer canonical models have been proven to provide an acceptable model for the human body. Highly similar return-loss characteristics have been found for implantable patch antennas inside a three-layer planar geometry and a realistic model of the human chest, as well as inside a three-layer spherical and an anatomical model of the human head.

V. STUDY OF EXPERIMENTAL PROCESS

Experimental investigations are required in order to confirm the validity of numerical simulations for implantable antennas. Since it is not possible to carry out measurements inside real operating scenarios (i.e., inside the human body), investigations are performed by measuring laboratory-fabricated prototypes inside either tissue-equivalent mediums (phantoms) or animal tissue [5].

PROTOTYPE FABRICATION

Due to the unavailability of biocompatible materials in some laboratories, other dielectrics with similar electrical properties may be selected for prototype fabrication. For instance, Rogers 3210 (ε r = 10.2, tanδ = 0.003) is often used because it has properties similar to the biocompatible ceramic alumina (ε r = 9.4, tanδ = 0.006) [6]. Prototype fabrication of implantable antennas meets all classical difficulties of miniature antennas. For example, additional glue layers used to affix all components together strongly affect antenna performance, by shifting the antenna's resonance frequency and degrading its matching characteristics.

Furthermore, the coaxial cable feed used to connect the antenna with the network analyzer may give rise to radiating currents on the outer part of the cable, which, in turn, deteriorate measurements. Based on the above, the numerical antenna model must be slightly adjusted in order to take prototype fabrication considerations into account. Numerical simulations and experimental measurements must be carried out with the exact same antenna structure in order to be able to validate the design.

TESTING INSIDE PHANTOMS

Testing inside phantoms is relatively easy and practical to implement. The fabricated prototype is immersed inside a tissue phantom (i.e., a container filled with a liquid or gel material that mimics the electrical properties of biological tissue), and measured. For validation purposes, the same scenario as that of the numerical simulations has to be considered. Recipes proposed mainly included deionised water, sugar, and salt[2].To prevent the formation of air bubbles and/or gaps, the mixture must be carefully heated and stirred, and slowly poured inside the container of the phantom. Since it is not possible to produce a valid approximation to human tissue for a broad frequency spectrum using a single formula, separate recipes are given for different frequency bands.

Measurements of the liquid's electrical properties (ε r and σ) are conducted by either the open-ended coaxial cable technique or a dielectric probe kit (e.g., Agilent's 85070E dielectric probe kit). As part of the experimental setup [7], prototype antennas are connected to a network analyzer through a coaxial cable, immersed inside the tissue-emulating phantom, and measured. A multilayer phantom is as shown in Fig. 1.4.

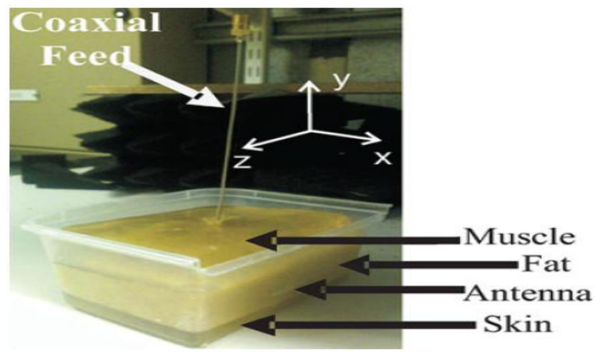

Fig.1. 4: A multilayer gel canonical phantom used for testing of implantable patch antennas

TESTING INSIDE ANIMAL TISSUE

Testing inside animal tissue can be performed either by embedding the implantable antenna inside tissue samples from donor animals, or by surgically implanting the antenna inside live model animals (in-vivo testing). In the first case, electrical properties of the test tissue can be measured using a dielectric probe kit and a network analyzer. The use of animal-tissue samples provides an easy approach to mimicking the frequency-dependency characteristics of the electrical properties of tissues. This can prove highly advantageous when carrying out measurements for multi-band implantable antennas. Fig 1.5 shows a triple-band implantable patch antenna that was tested inside a minced front leg of a pig.

Fig 1.5: Testing of an implantable patch antenna inside animal tissue: antenna surgically implanted into a rat.

In-vivo investigations are also vital in order to investigate the effects of live tissue on the performance of implantable patch antennas, while providing valuable feedback for antenna design and analysis.

VI. CONCLUSION

Implantable medical devices are a growing technology with a high potential for improving patients' life and the quality of healthcare. RF technology for implantable medical devices promises many benefits for both patients and caregivers.

Even though emphasis has been given to implantable patch antennas, it is worth noting that the shape of the implantable medical device and the intended implantation site will actually dictate the type of the antenna. Several methodologies have been proposed for implantable antenna design, all of which need to take into account the host body. Simplified tissue models have proven to be able to substitute for complex anatomical tissue models, thus speeding up simulations.

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