Antennas and Wireless Power Transfer to Small Biomedical Brain Implants

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Abstract— **In this paper and presentation, we will focus on different aspects of backscattering-based wireless communication and power transfer to small biomedical implants. We will present three different antenna topologies for data and power transfer through tissue, *in vitro* and *in vivo* studies on implantable intracranial pressure (ICP) sensors and give insight and analysis on wireless link reliability in tissue environment. We will also present radio frequency identification (RFID) -based implant platform and communication method. Moreover, we will focus on differences and challenges of *in vivo* environment compared to laboratory phantoms and tissue models. In our studies, different types of implantable antennas have been tested to investigate reliability, accuracy and sensitivity of the brain implants: a hybrid near field-far field system with a piezoresistive sensor for ICP monitoring, a UHF band spilt-ring resonator system and LC tank based miniature implantable antenna. This paper will present these implant antennas and wireless power transfer in tissue environment present in human head.**

Keywords— wireless biomedical implants, implant antennas, wireless power transfer

I. INTRODUCTION TO BRAIN IMPLANTABLE ANTENNAS

The major challenge in developing wireless brain implants is to establish a stable and efficient transcranial wireless link with the integrated implantable antenna. From the perspective of electromagnetics and wireless communications, human head is a complex dielectric environment comprising biological materials that are dispersive and characterized with relative permittivity and conductivity tens of times higher than materials present in regular electronics devices and wireless signal ambience. In addition, different tissue types differ in terms of their dielectric properties. Therefore, models combining multiple tissue types are required in electromagnetic modelling of implanted wireless devices. The brain implant typically needs a deep implant depth under the skull, usually at least 1.5 mm for neural signal recording and even several centimeters for deep brain stimulation. This deep implant depth with the highly lossy intracranial tissues surrounding the implantable antenna will affect the antenna's radiation efficiency and overall worsen the efficiency of the wireless link of the implant. To achieve a long-term implementation of the implant and minimize the biological intrusiveness causing scar tissue aggregating on the implant that potentially affects the implant performance, the implant should meet extreme structural requirements in terms of device miniaturization, thinness, and flexibility. These physical constraints pose strict requirements on antenna development in terms of size and shape.

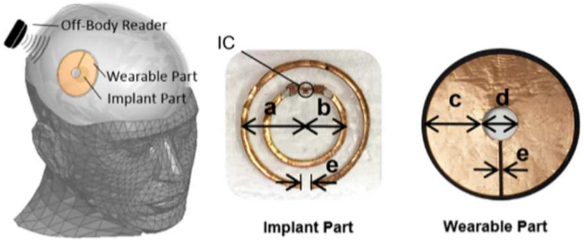
II. ANTENNA SYSTEMS

A. Hybrid Near Field – Far Field Antenna System

Intracranial pressure (ICP) is defined as the pressure inside the cranial cavity concealing three major volume components; blood, brain tissue and cerebrospinal fluid (CSF). The biological autoregulation of the cerebral blood flow and circulation of CFS maintains the stable ICP below 15 mmHg in adults. The ICP is an important indicator as the dysfunction of autoregulation and/or brain swelling that leads to intracranial hypertension and the increase of the ICP. The excessive ICP impedes the supply of oxygenated blood in the brain and causes brain damage. For this reason, the real-time monitoring of intracranial pressure (ICP) plays a crucial role in the management of various brain diseases and injuries. Currently, for the critically ill patients, the ICP is commonly measured from the ventricular system of the brain through a catheter. This method allows on-site recalibration as well as drainage of CSF to manage raised ICP, but is not fit for long-term monitoring due to its invasiveness. Therefore, several studies focused on the development of wireless implantable sensors for long-term monitoring of ICP are proposed. Authors of [1] present a battery powered sensor for ICP monitoring at 2.45 GHz. The main limitations of the battery power implantable sensors are the large size and limited life-time due to the battery. To address this limitation, passive ICP sensors are proposed in the literature. In [2], a transcranial implant integrated with the antenna and electronics for wireless monitoring of subdural pressures are proposed and demonstrated. To optimize the footprint of the implant and thus minimize the invasiveness, authors of [3, 4] developed capacitive MEMS based battery-free ICP sensors. These passive devices are small and flexible, however have limited functionality and short operation distance compared with the battery powered sensors. Alternatively, the batteryless ICP sensors equipped with the wireless power harvester is a potential minimally invasive solution to overcome the life-time and size limitation of the battery assisted method and the limited operation distance of the fully passive method. The work in [6] proposes the development of a batteryless wirelessly powered ICP sensor. The in-body unit has four parts including a 2-turns coil antenna for wireless powering, a rectifier for RF-to-DC conversion, a piezoresistive pressure sensor and a data transmission unit. The in-body unit is placed under the skull and powered by the on-body unit through inductive coupling. The piezoresistive pressure sensor has a differential output voltage which is proportional to the change in the pressure. When activated, this output voltage of the pressure sensor is amplified through an amplifier and drives the voltage control oscillator (VCO). Finally, the far-field antenna connected to the VCO output transmits the pressure readout to the off-body unit.

B. Split Ring Resonator-based Spatially Distributed Antenna System

Wireless electronic devices targeting for invasive biomedical applications need to meet the strict miniaturization requirement to minimize the invasiveness and reduce the risk of infections. This miniaturization requirement brings considerable challenge to the development of implantable antennas. Antennas with a miniaturized footprint inherently suffer from the low radiation efficiency and poor antenna directivity. When implanted in the lossy tissue environment, antenna RF performance becomes even worse. To obtain a proper antenna RF performance while maintaining a small size of the implantable antenna, a spatially distributed implantable RFID antenna system is proposed in [7]. The proposed antenna system has a small implant part carrying the RFID microsystem and an inductively coupled wearable part for antenna gain improvement.



Geometrical parameter (mm)	a	b	c	d	e
	8.6	5.7	20.8	12.6	1.0

Fig. 2. Geometry and dimensions of a split-ring based implantable antenna system [3].

Fig. 1 presents the antenna structure with its geometrical parameters and the implemented position in a layered ellipsoid model. The wearable part of the antenna system is attached on the scalp and the split ring resonator-based implant part is concentrically implanted in the CSF tissue layer. The implant part is developed on the 50 μm thick flexible polyimide substrate ($\varepsilon_r = 2.25$, $\tan\delta = 0.001$ at 915 MHz) and the substrate for the wearable part is 2 mm thick EPDM (Ethylene-Propylene-Diene-Monomer; $\varepsilon_r = 1.26$, $\tan\delta = 0.007$ at 915 MHz). The NXP UCODE G2iL series RFID IC as the target microsystem was attached to the inner ring split of the implant part using the conductive epoxy - Circuit Works CW2400. The silicone coating ($\varepsilon_r = 2.2$, $\tan\delta = 0.007$ at 915 MHz) with a thickness of 1 mm is used to insulate the antenna from the tissue environment.

C. LC Tank-based Miniature Implantable Antenna

The work proposed in [8] presents the design of an RFID antenna utilizing the coupled resonant LC-tank for antenna miniaturization. In the air, the size of the proposed antenna has been reduced to 0.04λ × 0.04λ × 0.02λ with a maximum read range of over 3 meters. We have implemented this LC-tank based RFID antenna for intracranial implantable applications. Fig. 2 shows the structure of the LC-tank based implantable RFID antenna with an anatomical head model. The proposed antenna is placed in the CSF layer with an implant depth of 16 mm.

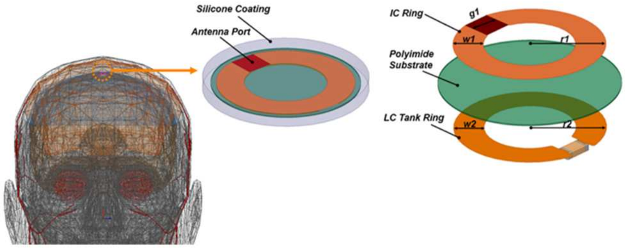


Fig. 2. Structure of the LC tank based implantable antenna system with anatomical head model [5].

The antenna is composed of two concentric copper split rings (IC ring and LC tank ring) with an outer radius of r1 and r2, respectively. The antenna port is located at the terminals of the IC ring. The terminals of the LC tank ring connect with a capacitor. The capacitance of the capacitor in series with the self-inductance from the copper ring together form the LC tank. The two rings are placed on the top and bottom sides of the 0.04 mm thick polyethylene (ε_r=2.25, $\tan\delta$=0.001 at 915 MHz), respectively. The insulation material used in this work is 0.5 mm thick silicone (ε_r=2.2, $\tan\delta$=0.007 at 915 MHz).

III. CONCLUSIONS

Wireless intracranial implantable devices will innovate the management of brain disorders and the treatment of neurological diseases. Over the past few years, various implantable antennas and wireless power transfer techniques have been proposed to establish the wireless through-body radio link for biomedical applications. Three different types of implantable antenna systems have been tested to investigate reliability, accuracy and sensitivity of the implants: hybrid near field-far field system with a piezoresistive sensor for ICP monitoring, UHF band spilt-ring resonator system and LC tank based miniature implantable antenna. The research work has especially addressed the following issues:

1. *Accuracy and reliability of the measurement:* We have investigated the accuracy and reliability of the passive sensors for ICP monitoring by comparing their measurements with

commercially available ICP monitors. The primary factors contributing to measurement error include thermal drift of the sensor, dynamic change of dielectric properties of the tissue, and accumulation of biological material around the sensing element. The latter might also impact the mechanical properties of the sensor's membrane. With the information gained from this study, we have an understanding of the in vivo sources of error and how to improve the measurement accuracy.

2. *Implantation and surgical challenges:* There are many considerations related to the surgical placement of the sensors and the associated complications. A properly engineered implant is required to reduce the risk factors of sensor malfunctioning/failure due to inappropriate placement. We have gained insights into the limitations and challenges of the implantation procedure, which will help in further optimization of the sensors for achieving the most clinically efficient and convenient implantation procedure.

To summarize, the results provide new understanding on the behavior of chronically implanted wireless brain sensors. Findings from this research can be utilized in numerous biomedical implant applications.

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