A Miniaturized Tunable Microstrip Antenna for Wireless Communications with Implanted Medical Devices

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Abstract**—** In this paper, a miniaturized microstrip antenna design is presented for establishing wireless communications with implantable medical devices in the 402-405 MHz Medical Implant Communications Services (MICS). The Ansoft's High Frequency Structure Simulator (HFSS) and CST Microwave Studio were used to evaluate the antenna design. HFSS is based on the Finite Element Method (FEM) and Microwave Studio is based on the Finite Difference Time Domain (FDTD) technique. The results from both simulations are compared to validate results obtained from the two software packages. A varactor diode is added to allow tuning of the antenna. Size reduction techniques such as meandering, addition of a shorting pin, and the introduction of a capacitive plate were investigated to make the antenna size suitable for use with medical implants.

*Keywords***—**Finite Element method, Finite Difference Time Domain, Medical Implants, Microstrip Antenna, MICS band, HFSS, Microwave Studio.

1. INTRODUCTION

DEBILITATING illnesses such as chronic heart failure, cancer, incontinence, and diabetes affect millions of lives worldwide. Medical personnel often use active implanted devices to monitor or treat patients with these illnesses. While passive implants, such as steel rods or prosthetic hip joints, aim to support the structure of the body, active implanted devices act as an involuntary organ of the body [6]. These active implants include pacemakers, intracardiac defibrillators, automatic drug pumps, brain and optical sensors, and automatic insulin injectors. They often consist of a power supply, storage/delivery system, and timing mechanism contained within a single biocompatible housing. Some implants are completely internal to the host; others are only partially internal and can be powered through wires from outside the body.

Active implanted medical devices (IMDs) need a communication link with an external monitoring/control unit. When an active IMD malfunctions, it is as if an organ of the body has failed. If a communication link between the IMD and the user is not available, then the only information that is accessible about how the implant is functioning inside the body comes from how the patient feels. Under such circumstances, unnecessary surgical procedures for IMD removal and replacement can be avoided through the use of a wireless communication link.

Currently, the majority of IMDs are not equipped with a wireless communications link; others are connected to the user via inductive coupling or wires. However, advances in MEMS, mix-signal circuitry, Radio Frequency (RF) components, and antennas have allowed for the development of more advanced forms of communication with IMDs [5]. Another driving force is that a globally accepted frequency band had been dedicated to medical implant device communications in the shared 402-405 MHz frequency band.

The MICS band is well suited for in-body communications due to the favorable signal propagation characteristics in the human body. Furthermore, the MICS standard allocates 300 kHz for each channel, which allows the design of high data rate (around 400 kb/s) communications links, compared with the low data rate (up to 500 b/s) that inductive coupling provides. This high data rate makes it possible to transmit sensory information with a very high resolution.

In this paper, we report an antenna design that has been developed by conducting simulations using HFSS and Microwave Studio. Another objective is to demonstrate the tuning capability of the designed antenna using a varactor diode. The antenna was first designed and simulated using HFSS, which is based on the well-known frequency domain, FEM. Then, the antenna was simulated using the FDTD-based time-domain solver of Microwave Studio.

Size reduction techniques such as adding a shorting pin, meandering the patch as well as adding a capacitance, have been utilized in order for the antenna to resonate in the MICS band while maintaining dimensions suitable for in-body use. Finally, a reversed-biased varactor diode was inserted and examined through a parametric study to investigate the achievable tuning range to maintain resonance within the MICS band when the antenna is situated in different positions within the human body.

2. DESIGN CONSTRAINTS

The antenna design has to satisfy three main criteria to be suitable for use with IMDs:

2.1 Size

A microstrip antenna within an IMD should be as small as possible so that it can fit within the IMD case or can be placed just under the skin of the patient's head. Based on recommendations from a neurosurgeon, the antenna should be 1.5 cm in diameter and 3 mm in thickness to be implanted subcutaneously [Personal Communication, Dr. Badee Adada, Neurosurgeon and Assistant Professor, University of Arkansas for Medical Sciences, Little Rock, Arkansas, 2005]

2.2 Operating Frequency

The antenna must operate within the MICS band. This means that the antenna should resonate in the 402-405 MHz frequency range with a bandwidth covering the MICS band.

2.3 Biocompatibility

The antenna must be biocompatible so that it does not harm the patient, and it must be durable so that the body fluids do not harm the antenna. This entails the use of a superstrate. Alumina was selected for the substrate and superstrate because of its high permittivity, high thermo-conductivity and durability [4]. Alumina has been used in medical application since the 1970's and is currently still the material of choice for many hip replacement prosthetics because of its durability in rough weight bearing joints, scratch resistance, and hydrophilic nature, which results in reduced wear and reduction of particle load to the surrounding soft tissues [1].

3. DESIGN METHODOLOGY

A circular microstrip antenna, for which experimental data have been reported in the literature [8], was chosen initially to benchmark the design of the implantable antenna. For validation purposes, results obtained from HFSS were compared against the measurements reported in [8]. Table 1 compares the measured resonant frequencies reported in [8] against those obtained from HFSS for different meander lengths as shown in Fig.1. As seen from Table 1, the difference between the measured results and those obtained from HFSS is negligible. This asserts the validity of HFSS for analyzing the antenna structures under consideration.

The design was then adapted to resonate in the MICS frequency band in an open-air environment. Next, anatomic models for the human head were created and the antenna was placed just under the skin of the head. The antenna was subsequently inserted into the human head model and further modified to allow for resonance within the MICS band and to match the input impedance of the antenna to a 50-Ω feed

3.1 Validation: Antenna Design in a Free Space Environment

Figure 1 depicts the parameters of the antenna geometry simulated using HFSS for different meander lengths.

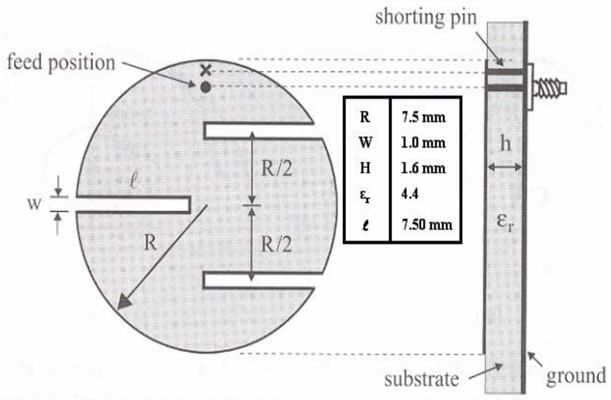
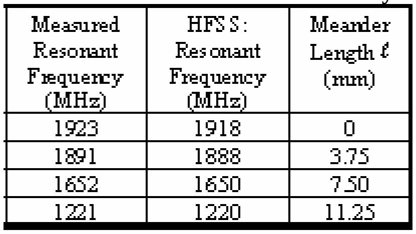


Figure 1. Geometry of the validation test

Table 1: Results of Validation Study



Measured Resonant Frequency (MHz)	HFSS: Resonant Frequency (MHz)	Meander Length ℓ (mm)
1923	1918	0
1891	1888	3.75
1652	1650	7.50
1221	1220	11.25

The antenna was first designed in a free space environment. Because the antenna is to be implantable, Alumina was used for both the substrate and superstrate. The thickness of the substrate and superstrate was chosen to be 1.5 mm, to maintain a total thickness that does not surpass the size constraints. In order to reduce the resonant frequency, the number of meanders seen in Fig. 1 was increased, the meanders were lengthened, the shorting pin position was changed and a capacitive plate terminated the patch. The antenna design is shown in Fig. 2. In this design, we have implemented a new printed capacitor (Fig. 2, inset). The detailed dimensions are given in Table 2. These modifications reduced the resonant frequency of the antenna shown in Fig. 2 to 388 MHz while the antenna is radiating in air using simulations in HFSS.

Table 2: Meander lengths of the antenna shown in Fig.2

Meander	Length (mm)
1	6.912
2	10.383
3	13.321
4	13.495
5	13.321
6	10.383
7 Fig. 4 only	6.912

The meander numbers start at the bottom of the antenna in Fig. 2 with the small meander and increase in number from bottom to top. Meander 7 was added to the antenna in Fig. 4.

The antenna, shown in Fig. 2, was further simulated in Microwave studio, which yielded a resonant frequency of 384 MHz. This shows a very close correspondence between the results obtained from the two software packages, which are based on entirely different formulations, and hence validates the precision of the numerical results.

Next, the capacitor plate was removed and a meander arm was added to make the antenna symmetric as shown in Fig. 4. These changes shifted the resonant frequency to 491.5 MHz, as shown in Fig. 5. Another approach we used to adaptively tune the antenna, while implanted inside the human head, involves the use of a varactor diode, the reverse biased voltage of which could be changed externally. In order resonate in the 402-405 MHz band; we propose to tune the antenna in a controlled scheme. When operating in a reverse bias, the varactor diode functions as a capacitor. A microcontroller will be utilized to provide the exact voltage needed for the specific capacitance required from the diode.

We have performed a parametric study to investigate the tuning range that could be achieved using data from a family of varactor diodes [2] to provide accurate capacitance values for the simulations. Results depicted in Fig. 6 show that a capacitance of 3.2 pF allows the antenna to resonate in the 402-405 MHz band. The reverse bias voltage can be changed to achieve the desirable capacitance within the particular diode's voltage region, thus providing a relatively wide tuning range. This methodology allows tuning the antenna when implanted in different positions within the human body.

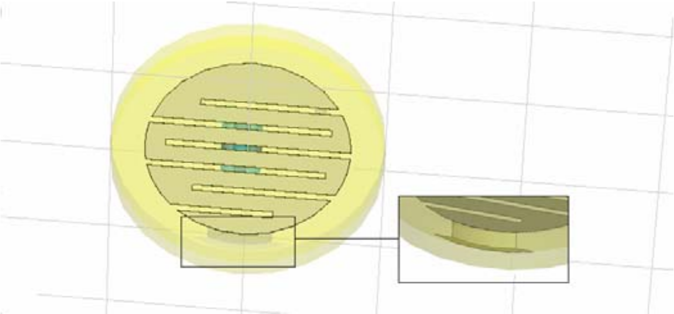


Figure 2. Original model in air environment

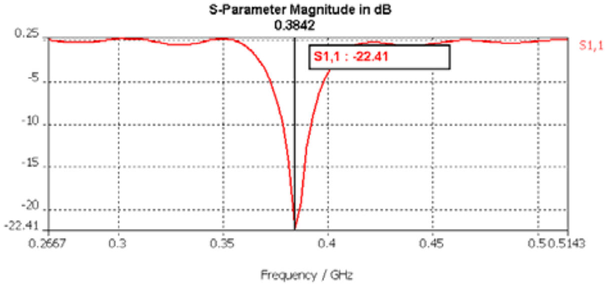


Figure 3. Reflection coefficient of the Fig. 2 antenna in free space

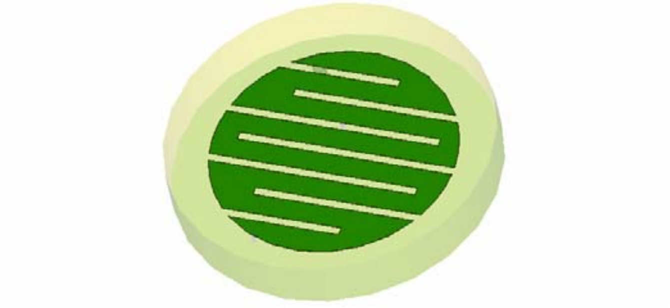


Figure 4. Final antenna model in an air environment

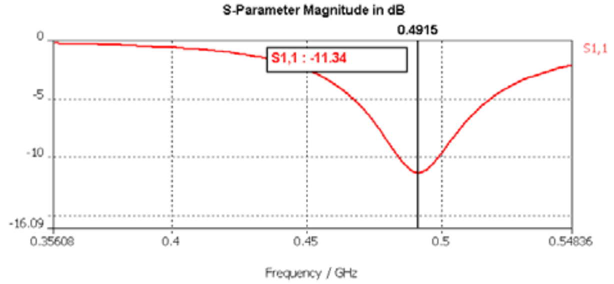


Figure 5. Reflection coefficient of the antenna shown in Fig. 4 without diode radiating in free space

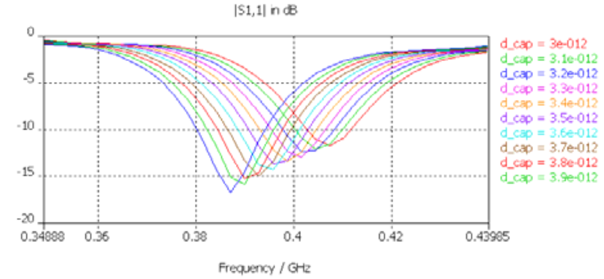


Figure 6. Parametric study of the reflection coefficient of the antenna shown in Fig. 4 loaded with a diode and radiating in free space

3.2 Testing in a Hugo Human Mesh

The antennas shown in Figs. 2 and 4 were implanted into the Hugo Human Mesh [7] as seen in Fig. 7 in order to characterize the effects of the surrounding tissues on their radiation properties, in particular the resonant frequency. This model uses voxel data imported into Microwave Studio from the staircase Hugo mesh. A staircase mesh of 2mm × 2mm × 2mm was used to provide a high degree of spatial resolution in the simulation. The staircase mesh allowed by Hugo could be as large as 8mm × 8mm × 8mm and as small as 1mm × 1mm × 1mm. The 2mm size was chosen to allow for reasonably accurate results while maintaining an acceptable simulation time. Implementing the antenna model into the Hugo mesh adds millions of cells, depending on the size of the voxel cubes.

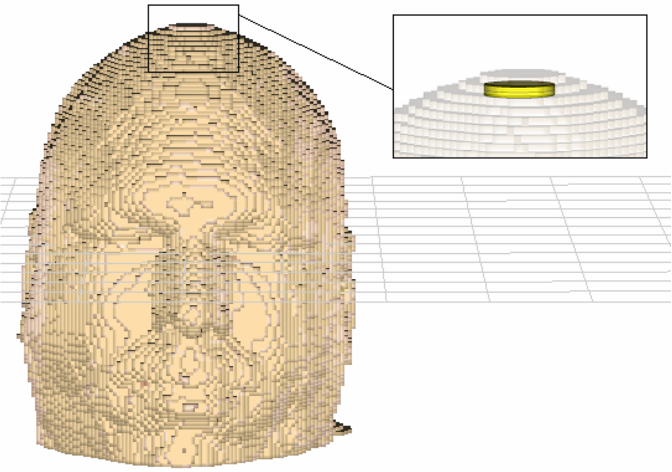


Figure 7. Hugo head model showing placement of antenna within tissue layers

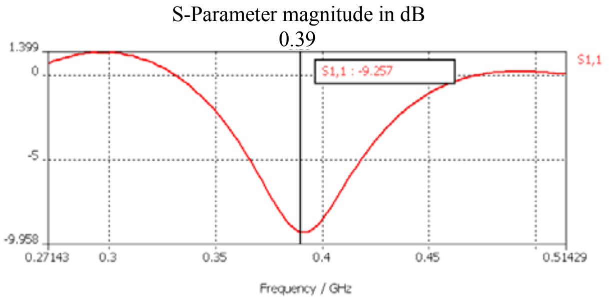


Figure 8. Reflection coefficient of the antenna shown in Fig. 2 when implanted in the Hugo human head model

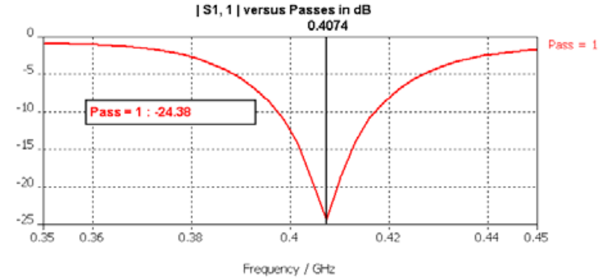


Figure 9. Reflection coefficient of the antenna shown in Fig. 4 loaded with a diode implanted in the Hugo head model

The reflection coefficient of the antenna (Fig. 2) implanted in the Hugo human head model is presented in Fig. 8. It should be noted that the resonant frequency in the Hugo model has increased from 384 MHz to 390 MHz (Fig. 8). This is due to the capacitive loading effect of the surrounding tissues. This shows the need for the antenna to be tuned while implanted in the head. The varactor diode provides the tuning capability.

The antenna of Fig. 4 was loaded with a diode and then implanted into the Hugo human head. A capacitance value of 3.2 pF was used for the diode for the first simulation. As can bee seen from the results shown in Fig. 9, the results are quite comparable to the results shown in Fig. 8. The resonance of the antenna shown in Fig. 9 shifted up by approximately 4 MHz, which is very similar to the shift of 6 MHz displayed in Fig. 8. To bring the resonant frequency shown in Fig.9 within the 402-405 MHz band, the capacitance would only have to be increased by 0.1 - 0.2 pF to yield a capacitance of 3.3 - 3.4 pF. In the simulation, it was found that 3.3 pF was sufficient, but 3.4 pF was also acceptable. These values are acceptable within the specifications of diodes available in the market [2].

4. CONCLUSION

This paper examined a compact implantable microstrip antenna for use within the human head. The paper demonstrates the feasibility of tuning implantable microstrip antennas by using a varactor diode. Overall findings suggested that a microstrip antenna of this design may have true merit in medical applications and future studies are warranted. Work is in progress to address the specific absorption rate, temperature induced within the surrounding tissues, and experimental characterization of the antenna in different operating environments. Work is also in progress to address the gain required to achieve the link budget of the wireless system to satisfy the detection threshold of commercial transceivers.

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