Analysis of Milimeter-Size Implanted Loop Antennas for Brain-Machine Interface Systems

Lingnan Song, and Yahya Rahmat-Samii
Department of Electrical Engineering
University of California, Los Angeles
Los Angeles, CA
lingnan.soong@gmail.com, rahmat@ee.ucla.edu

***Abstract*—Brain-machine interface (BMI) is a multidisciplinary field that has enormous potential to help large numbers of people suffering from a wide variety of disabling neurological conditions. To achieve that, such systems require a wireless link for the implanted neural sensors to communicate with external unit that decodes neural data and controls prosthetic limbs. We have characterized miniature millimeter-size implantable antennas that are capable of communicating with a transmitting antenna outside human body. The wireless link present in the full human head model was simulated in ANSYS HFSS. Prototype antennas are fabricated and functionalities are analyzed by measurements. Operating at the medical implant communications service (MICS) frequency band (402–405 MHz), such novel antennas provide low cost and low power solutions for wireless and passive neural interfaces for BMI technology.**

I. INTRODUCTION

Brain-machine interface (BMI) technology holds great potential for patients suffering from a wide variety of severe neurological conditions, such as paralysis, stroke, and spinal cord injury. BMI systems record neural data and transform thought into action, which fulfill the dream of many patients – living independently, using prosthetic limbs in the same way as biological ones. Such systems require sensors for neural recording, programs for brain simulation, and finally, a wireless link to communicate with external unit that decodes neural data and controls prosthetic limbs [1]. Development of wireless, ultra-low power, bi-directional and fully implantable neural interfaces plays key role in this endeavor. Currently, powering and communicating with miniature implants reliably remains a major challenge that needs to be overcome [2]. Near-field inductive coupling is one of the most promising methods to establish wireless powering for implanted microsystems.

In this paper, we present miniature millimeter-size implantable antennas that could communicate with an external transmitting antenna near human head at the MICS frequency band (402–405 MHz) [3]. Theoretical analysis of the wireless inductive link between a low-profile interrogator loop antenna and the implanted antenna is presented first, followed by discussion focusing on antenna design of transmitting and implanted loop antennas to achieve high magnetic coupling and low SAR. Simulation results of the coupling link power efficiency between transmitting and implanted antennas presented in human head model are shown, proving the feasibility of this approach. This work was inspired by the research done by a group in Finland [2].

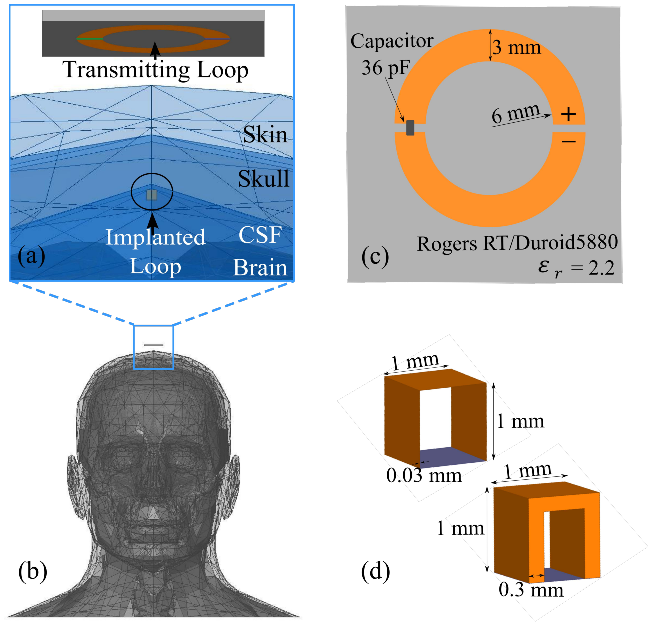

Fig. 1. Simulation of wireless link formed by mm-size implanted antenna and low-profile transmitting antenna. (a) Transmitting and implanted loops modeled in ANSYS HFSS and (b) full image of antennas with human head model. (c) Planar structure of segmented transmitting loop antenna and (d) 3-D structure of mm-size implanted cubic loop antennas.

II. WIRELESS LINK CHARACTERIZATION

Power is transferred from outside to the implants by short-range backscattering technology using near-field inductive links with loop antennas, which is a desirable method to transfer power efficiently through short distances and highly dissipative media, such as human head. A wireless inductive link between transmitting and implanted loop antennas can be characterized as a linear microwave two-port network. The effective coupling between antennas can be described by link power efficiency $G_{p,max}$, which is defined by the maximum ratio of the power delivered to the implanted microsystem to the power supplied to the external transmitting antenna, achieved as the input and output ports are simultaneously conjugate matched. In the case of near-field coupling, the link power efficiency $G_{p,max}$ can be represented in terms of the two-port Z parameters as [4]:

$$G_{,max} = \frac{|z_{21}|^2}{S+\sqrt{S^2+|z_{12}z_{21}|^2}}, \text{ where} \quad (1)$$

$$S = 2Re(z_{11})Re(z_{22}) - Re(z_{12}z_{21}). \quad (2)$$

Here the subscript 1 refers to transmitting port and subscript 2 refers to implanted port. In the above equations we assume that coupling between loops are relatively small ($|z_{12}z_{21}| \approx 0$) [4], and transmitting and implanted antenna ports are conjugate matched with source and implant IC, respectively.

The wireless link between transmitting and receiving loop antennas was modeled in ANSYS HFSS 15.0. The present of human tissue was simulated using ANSYS human head model (2 mm accuracy). As shown by Fig.1 (a) and (b), the implanted loop antenna was immersed in cerebrospinal fluid (CSF) surrounding the brain, and the transmitting antenna was arranged about 10 mm on top of skin.

III. MODELING OF ANTENNAS

A. *Transmitting Antenna*

On the transmitting antenna side, the challenge is to design transmitting loop that provides high inductive coupling with the implanted loop as well as low near electric field, which means low specific absorption rate (SAR) compliant to FCC regulation. Prior research has demonstrated that by partitioning the transmitting loop into segments and inserting capacitors within the gaps, electric-field hot spots in human tissue can be removed effectively [1]. Thus, in this study, we used a 2-segmented planar copper loop structure for transmitting antenna and connect the segments with 36 pF capacitor. As shown in Fig. 1(c), antenna was simulated and fabricated on a 31-mil Rogers RT/Duroid5880 substrate ($\varepsilon_r = 2.20$) with 6-mm inner radius and 3-mm trace width, which were optimized to achieve high coupling with the implanted loop at the MICS frequency band of 402–405 MHz and the given separating distance of 15 mm.

B. *Implanted Antenna*

The implantable antenna should be bio-compatible and miniaturized without increasing the size of the implanted system significantly. Thus, ultra-compact antennas are desirable solutions for localized neural recording systems. Here we used 1-mm^3 3-D cubic loops in copper (Fig. 1(d)), which provides wider current path and larger coupling area compared to their planar counterparts with the same cross-section area. This is a modified version of the design in [2]. Effect of copper thickness was studied by comparing two models with same outer dimensions but different in copper thickness (0.03 mm and 0.3 mm). Fig. 2(a) shows the simulated link power efficiency of the 1-mm^3 implanted loops coupling with the planar transmitting loop described in the former section, which was generated by the simulated two-port Z parameters extracted from ADS models and was calculated through (1) and (2). The implanted loops were aligned at the lateral center of transmitting loop with vertical distance of 15 mm. Here we model the wireless link in air. Results with the presence of human head could decrease by around 2 dB from what we demonstrate here. We also observe a 2-dB enhancement in coupling efficiency of the link with 0.03-mm thick implanted loop, comparing with the 0.3-mm counterpart.

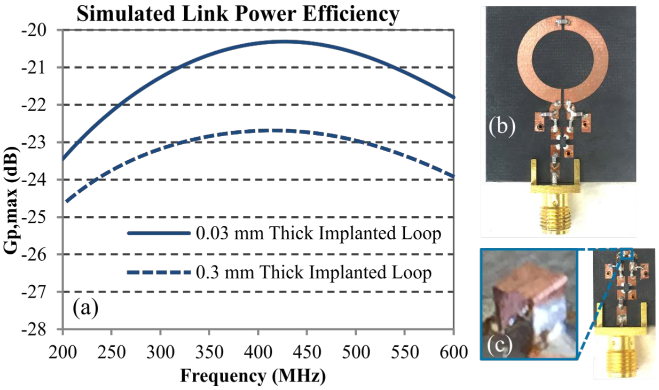

Fig. 2. (a) Simulated link power efficiency of implanted loop antennas (0.03-mm and 0.3-mm thickness) coupling with 2-segmented planar transmitting loop antenna. (b) 2-segmented transmitting antenna prototype and (c) 1-mm^3 implanted antenna protptype, with matching networks embeded.

IV. ANTENNA FABRICATION AND MEASUREMENT

Transmitting and implanted antenna prototypes were built as described in the previous section (Fig. 2(b) and (c)). In order to test the functionality, we also implemented matching networks using lumped capacitors to match the complex antenna impedances to the characteristic impedance of VNA (50 Ω) at 403 MHz. Surface-mount baluns were included in the circuits to convert differential port of antennas to single-feed port connected to VNA. The matching networks were designed using ADS2014, with the S parameters extracted from antenna simulations in HFSS. Preliminary testing results demonstrate S11 and S22 below -10 dB at frequency around 403 MHz. Future work will involve 2-port measurement of link power efficiency conducting in liquid phantom.

ACKNOWLEDGEMENT

The authors would like to thank the research group of Prof. Leenna Ukkonen at Tampare University, Finland for their cooperation.

REFERENCES

[1] E. Moradi, K. Koski, T. Björninen, L. Sydänheimo, J. M. Rabaey, J. M. Carmena, Y. Rahmat-Samii, L. Ukkonen, "Miniature implantable and wearable on-body antennas: towards the new era of wireless body-centric systems", IEEE Antennas Propag. Mag., vol. 56, no. 1 , pp. 271-291, Feb. 2014.

[2] E. Moradi, S. Amendola, T. Björninen, L. Sydänheimo, J. M. Carmena, J. M. Rabaey, L. Ukkonen, "Backscattering neural tags for wireless brain-machine interface systems," IEEE Trans. Antennas Propag., vol. 63, no. 2, pp. 719-726, Jan 2015.

[3] Y. Rahmat-Samii and J. H. Kim Implanted antennas in medical wireless communications, Synth. Lect. Antennas, vol. 1, no. 1, pp.1 -82 2006

[4] E. Moradi, T. Björninen, L. Sydänheimo, L. Ukkonen, and J. M. Rabaey, "Analysis of wireless powering of mm-size neural recording tags in RFID-inspired wireless brain-machine interface systems," presented at the IEEE RFID Conf., Orlando, FL, USA, Apr. 30–May 2, 2013..