MEMS-Based Inductively Coupled RFID Transponder for Implantable Wireless Sensor Applications

Hong M. Lu[1], Chuck Goldsmith[2], Lawrence Cauller[3], and Jeong-Bong Lee[4]

[1]Luminus Devices. Inc, Woburn, MA, 01801 USA
[2]MEMtronics Inc., Plano, TX, 75081 USA
[3]School of Behavioral and Brain Sciences, University of Texas at Dallas, Richardson, TX 75080 USA
[4]Department of Electrical Engineering, University of Texas at Dallas, Richardson, TX 75080 USA

In this paper, we present the development of an inductively coupled mini RFID transponder using MEMS technology for implantable wireless sensor applications. The transponder (approximately 25 mm^3 in volume) consists of a small solenoid inductor with a high-permeability magnetic core $(\mathrm{dia.} = 750\ \mu\mathrm{m})$, a chip capacitor and a RFID chip. They are integrated onto a micromachined SU8 polymer substrate and it is operated in the frequency range of 13.56–27 MHz. Voltages up to 4 V were obtained at a small 0.5 μH transponder coil from a 2.2-μH reader coil at 5 mm distance based on a resonant magnetic coupling mechanism. The assembled transponder was tested using a commercial RFID reader at 13.56 MHz and successful communication was established at a distance of 10 mm.

***Index Terms*—Implantable, MEMS, RFID, sensor, transponder.**

I. Introduction

RADIO frequency identification, or RFID technology, has seen extensive deployment in manufacturing, asset tracking, and public transportation. Implantable RFID tag (transponder) has been used for live stock tracking for many years. Recent development in this technology for different medical applications such as linking the patient to key drugs, patient identification, and health information has evoked enormous interests [1]. The wireless data transmission between the monitoring device (sensor) and the data capturing device (reader) offers the advantage in eliminating the need of wires or direct contact, which makes it suitable for implantable purposes.

In an inductively coupled RFID system, as both data and power can be exchanged through the mutually coupled magnetic field between the reader and the transponder coils, elimination of the transponder's power source suggests that it can be built very small in size and work reliably based on the coupled energy from an external source for an extended period of time. As the demand towards smaller implantable device grows, MEMS (micro-electro mechanical system) technology could be a strong candidate for integrating miniaturized mechanical components and electronics to construct a complete transponder in submillimeter scale. In this study, we present the development of a MEMS-based, inductively powered transponder in millimeter scale operate at 13.56–27 MHz which uses a small, low inductance solenoid inductor as its coupling element. The ultimate objective is to build a transponder in submillimeter scale integratable with an already developed micro neuron sensor implanted in subcutaneous level (depth $\leqslant$5 mm) to function as a backscatter-based implanted wireless sensor.

Our study is divided into two sections. HFSS® (*Ansoft Corp.*, Pittsburgh, PA) high-frequency simulation software is first deployed to figure out an adequate reader-transponder coil layout in creating an optimal magnetic coupling in order to maximize the induced voltage (v_T) at the micro transponder coil. In the second part of this paper, a millimeter scale transponder is developed based on a micromachined plastic package at this stage as a demonstration and test bed for the future micro transponder.

Digital Object Identifier 10.1109/TMAG.2007.893802

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

II. Computer Simulation on Magnetic Coupling

Theoretically, the induced voltage (v_T) at the transponder coil through the time-varying magnetic field from the reader coil can be determined as [2]

$$\nu_T = \frac{\omega \cdot k \cdot \sqrt{L_T L_R} \cdot i_R}{\sqrt{\left(\frac{\omega L_T}{R_L} + \omega R_T C_T\right)^2 + \left(1 - \omega^2 L_T C_T + \frac{R_T}{R_L}\right)^2}} \quad (1)$$

where ω is the working frequency in radian/s; L_T and L_R represent the transponder and the reader coil inductance, respectively. k denotes the coupling coefficient between the two coils, and i_R denotes the current flow in the reader coil. R_T is the series resistance of the transponder coil at the working frequency. R_L and C_T depict the load resistance (transponder chip) and the matching capacitance in making the parallel resonant circuit, respectively. From the formula, enhancement in mutual inductance $(k \cdot \sqrt{L_T L_R})$ is highly desirable in obtaining higher coupled voltage at a given frequency and input reader transmission power level; as current in the reader coil can be found as the input power P_{in} and the reader coil series resistance *Rs* as $i_R = \sqrt{(2 \cdot P_{\mathrm{in}}/R_S)}$.

A. Effect of Transponder Coil Core's Relative Permeability

High-quality magnetic core can be deployed in a micro inductor to improve its inductance [3] and subsequently, the magnetic coupling between the coils in an inductively powered RFID system. In simulation, a 20-turn micro solenoid coil with a square core dimension of 200 μm × 200 μm, and a length of approximately 500 μm is designed to be the transponder coil. The circular magnetic core contained has a diameter (d) of 180 μm and also a length (l) of 500 μm. The 10-turn solenoid type reader coil has a mean radius of 7 mm and a simulated inductance of 2.2 μH. In simulation, relative permeability (μ_r) from 1 (air core) to 2000 are applied to the core material. The coupling coefficient (k) and transponder coil inductance (Ls_2) are plotted in Fig. 1. Higher core permeability effectively improves both the inductance and the coupling at the beginning. The growing rates for the two parameters, however, decrease as the core's μ_r goes higher and become nearly constant beyond the point where $\mu_r = 500$. The primary reasons can be contributed to the core dimension in nature and its geometry $(l : d = 2.78 : 1)$. According to [4], the effective permeability of a magnetic core is deeply influenced by its length to diameter ratio. Therefore, at a give diameter, longer core will be

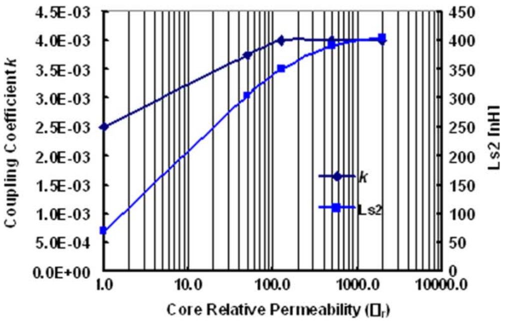

Fig. 1. Simulation result of coupling coefficient (k) and transponder coil inductance $(Ls2)$ as a function of the transponder coil's core relative permeability (μ_r) at a vertical distance of 5 mm. The growing rate for both quantities becomes lower for the core permeability higher than 100.

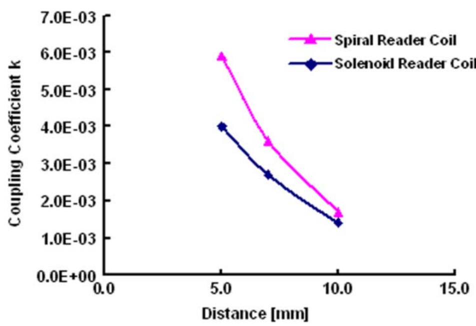

Fig. 2. Simulation result on coupling coefficient (k) as a function of vertical distance for both solenoid and planar spiral reader coil designs. Planar spiral reader coil produces stronger coupling than that of the solenoid design at the same distance; the difference is more significant at shorter range.

more efficient in enhancing a coil's inductance. In our study, longer core is not applicable due to geometrical restriction. This finding indicates that magnetic core material with very high permeability is not necessary to enhance the inductor performance; which is beneficial as such materials usually experience heavier loss as the operating frequency increases.

B. Effect of the Reader Coil Design

Since the transponder coil's length and diameter is limited by its implantable nature, the design of the reader coil plays a very important role in influencing the magnetic coupling. According to Biot-Sarvart Law

$$B_P = \frac{\mu_0 I}{2} \cdot \frac{a^2}{(a^2 + d^2)^{3/2}} \hat{z} \tag{2}$$

where a and d denote the coil radius and vertical distance, respectively; the optimal a for creating the strongest B field along the coil center axis can be determined at a given d. In our case the optimal reader coil radius is found to be around 7 to 8 mm at the interested distance of 5 mm. In an effort to improve the magnetic coupling, a planar spiral type reader coil has been implemented and the simulation results on k and Ls_2 are plotted in Fig. 2 as a function of vertical distance in comparison with the solenoid type reader coil. In simulation, both reader coil designs have the same mean radius and are wound with copper wire 300 μm in diameter and having 100 μm spacing between adjacent turns. The 10-turn spiral coil has a simulated inductance of 2.1 μH, which is similar to that of the 10-turn solenoid coil. The transponder coil in this simulation lies coaxially to the reader coil and has the same geometry described in section A. It also contains a magnetic core which has a relative permeability of 125; a diameter of 180 μm and a length of 500 μm.

The plot clearly shows that the planar spiral reader coil has a stronger coupling with the transponder coil than that of the solenoid design at the same distance. The difference becomes smaller as the distance increases. This is understood since the coil radius is optimized only for the 5 mm distance. Therefore, more concentrated B field can be expected at the same point by arranging all the reader conductor loops into one plane. As a result, stronger magnetic coupling and consequently higher transponder voltage can be achieved.

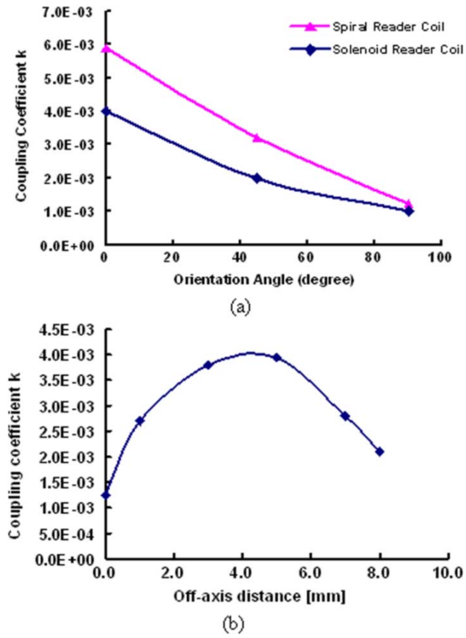

Fig. 3. Simulation results show the effects of transponder coil's rotational angle and position with respect to reader coil in coupling coefficient k. (a) At 5-mm distance along the reader coil's center axis, k drops quickly as the rotational angle increases and reaches the minimum at 90°; and (b) stronger coupling (higher k) can be approached by shifting the transponder coil horizontally to near reader coil's edge at a 90° rotation angle.

C. Effect of the Transponder Coil's Orientation

The coupling can be considered at its peak when two coils are placed in a coaxial configuration; and it would drop once a coil's orientation angle starts to change with respect to another. It is our interest to find out how the orientation angle of the transponder coil would affect the magnetic coupling; and how the transponder should be deployed if the two coils are lying perpendicular to each other to maintain an adequate coupling level. Since for our application, the transponder coil is unlikely to remain in a perfect coaxial alignment with the reader coil after implantation. From simulation plots, substantial drop in coupling coefficient can be observed as the transponder coil orientation angle with respect to the reader coil increases from 0° (coaxial) to 90° (perpendicular) at a 5 mm vertical distance, as shown in Fig. 3(a).

The difference in k is minor between spiral and solenoid reader coil designs in this case since mathematically, the common magnetic flux area between the reader and the transponder coils is 0. However, due to the nature of the bending flux lines, this situation can be improved by shifting the transponder coil away from the center to (or near) the edge of the reader coil. In Fig. 3(b), more simulations show that for a transponder coil which is perpendicular to the reader coil, it experiences stronger coupling as it moves towards the reader coil's conductor loops and the coupling peaks once it is near the top of the conductor loops. The coupling then drops again as the transponder continues moving further away from the reader coil. Therefore, a transponder should be deployed along the reader coil center axis if they are in a coaxial arrangement. And it should be placed near the top of the reader coil's conductor

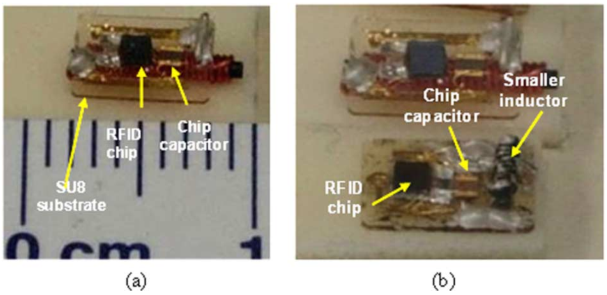

Fig. 4. Completed millimeter scale transponders built on micromachined SU8 plastic package which is measured 8 mm × 3 mm in dimension. (a) A transponder that deploys a 2.2-μH solenoid inductor as its coupling element; the inductor has a core diameter of 750 μm and a length of 8 mm; and (b) New transponder that has a 0.5-μH inductor as its coupling element; the inductor has a core diameter of 750 μm and a length of 3 mm.

loop if it is perpendicular to the reader coil in order to maintain an adequate coupling.

III. Device Demonstration and Experimental Results

In order to demonstrate the micro transponder concept, a millimeter scale transponder is built on a micromachined plastic package as a test bed at this stage. The 20-turn, 2.0 μH mini transponder coil used in this experiment contains a commercially available magnetic core which is 750 μm in diameter and 8 mm in length; and holds a μ_r of 125. The mini coil is first attached to a micromachined plastic packaging substrate made of SU8 photo resist (*Microchem Inc.*, Newotn, MA) by conductive epoxy. A chip capacitor is then wire bonded to the same substrate in parallel connection with the mini coil to form a LC resonant circuit. The capacitance value is picked so that the parallel LC circuit would resonate at the same operating frequency of 13.56 MHz as the reader resonant circuit. The actual resonant frequency of the circuit is examined by using a HP8756 scalar network analyzer (SNA) and a HP8350B frequency sweeper oscillator. Finally, a commercial RFID chip is assembled to the plastic substrate by wire bonding to complete the transponder. The finished device is shown in Fig. 4(a). The overall dimension of the device is measured approximately 8 mm × 3 mm.

In order to measure the coupled voltage v_T, a 10-turn planar coil with mean radius of 7 mm and a measured inductance of 2.2 μH is first connected to the SNA as the reader coil. The millimeter scale transponder is held to the reader coil coaxially at an approximate distance of 5 mm. The induced voltage at transponder coil is measured by an oscilloscope as a function of SNA's input power and the test data is plotted in Fig. 5 (blue line). The same experimental set up is also simulated in HFSS and the computed v_T based on the simulated coupling coefficient is also plotted in Fig. 5 (purple line).

The discrepancy between the computed and the measured values could be caused by several factors. First of all, the distance between the transponder and the reader coil could be slightly larger than 5 mm during the experiment and distance is one of the most important factors affecting the coupling. Second, not all the losses were taken into consideration during simulation and thus affecting the accuracy of the output. Overall, the simulation data provides a reasonable match to the measurement results.

The assembled transponder in Fig. 4(a) is tested by a commercial RFID reader at 13.56 MHz and successful data transmission

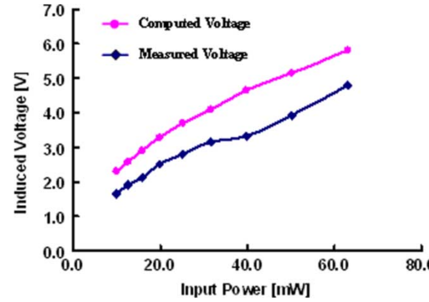

Fig. 5. Calculated and measured inductively induced voltage (v_T) for the assembled transponder shown in Fig. 4(a) as a function of the reader coil's input power at a working frequency of 13.56 MHz and a distance of 5 mm; the transponder and the reader coils are in a co-axial arrangement.

is established at approximately 10-mm range. New transponder, which utilizes an even smaller coil as the coupling element, as shown in Fig. 4(b), is designed to operate at a much higher frequency of 27 MHz. A maximum v_T of nearly 4 V is achieved on oscilloscope when it is positioned coaxially with the reader coil at 5 mm, with SNA's input power at 65 mW.

IV. Conclusion and Future Works

In this paper, a study on an inductively coupled, MEMS-based micro RFID transponder for potential implantable sensor application and an experimental demonstration of millimeter scale micromachined RFID have been carried out. Based on simulation results, it was found that improvement in inductance drops sharply as μ_r becomes higher than 125 for the given micro coil's core geometry. It was also found that the planar spiral shape reader coil provides better coupling than solenoid reader coil with equivalent dimension and inductance at the same distance. If the transponder coil is placed perpendicular to the reader coil, the coil must be placed near the top of the reader coil to enhance the coupling. Millimeter scale transponders have been realized on a micromachined SU8 plastic package and characterized. Successful data transmission between the millimeter scale transponder and a commercially available RFID reader has been demonstrated at the frequency of 13.56 MHz and a distance of 10 mm. In addition, a millimeter scale micromachined RFID (< 25 mm^3) with a small inductor (0.5 μH) showed a maximum coupled v_T up to 4 V at 27 MHz with and 65 mW RF power. Experimental verification of the micro RFID (< 6 mm^3) work is currently under way.

Acknowledgment

This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) under Contract N66001-05-C-8029. The authors would like to thank S.-H. Cho at the University of Texas (U.T.) at Dallas and U.T. Dallas Clean Room staffs for their support in this work.

References

[1] [Online]. Available: http://www.rfidjournal.com/article/view/2662
[2] K. Finkenzeller, *RFID Handbook*. Hoboken, NJ: Wiley, 1999.
[3] Y.-S. Kim, S.-C. Yu, H. Lu, J. B. Lee, and H. Lee, "A class of micromachined magnetic resonator for high-frequency magnetic sensor applications," *J. Appl. Phys.*, vol. 99, no. 8, 2006.
[4] [Online]. Available: http://www.amidoncorp.com/aai_ferriterods.htm

Manuscript received November 1, 2006; revised February 3, 2007 (e-mail: hlu@luminus.com).