FEA Simulation of Thin Film Coils to Power Wireless Neural Interfaces

S. Kim[*], O. Scholz[**], K. Zoschke[***], R. Harrison[*], F. Solzbacher[*], M. Klein[***], M. Toepper[***]

[*]Dept of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA
[**]Fraunhofer Institute for Biomedical Engineering, St. Ingbert, Germany
[***]Fraunhofer Institute for Reliability and Microintegration, Berlin, Germany

ABSTRACT

To wirelessly transfer energy into active biomedical devices such as neural stimulators or bio-monitors implanted in the body, magnetic coupling of a pair of coils are often used. In order to design such power coils, an exact modeling and prediction of their electrical characteristics is essential prior to the fabrication when the coils should be fabricated through micromachining technologies to achieve small size and enough efficiency. This paper describes modeling and simulation methods to predict the electrical characteristics of thin film microcoils based on finite element analysis methods. Not only the inductance and quality factor of coils, but high-frequency effects such as skin and proximity effects as well as parasitic capacitances can be predicted. Based on the simulation results, strategies to design microcoils are suggested in the viewpoint of power transmission efficiency.

Keywords: microcoil, finite element analysis (FEA), neural interface

1 INTRODUCTION

Recently, there have been efforts to develop fully integrated, wireless neural recording devices based on the conventional Utah Electrode Array [1]. To this end, these devices are required to be small enough not to disturb the living body by implantation and capable of functioning with no wire connections to any extracorporeal devices to avoid any infection associated with wire penetrations through the skin. Inductive coupling between two coils can be a solution to provide power to the integrated electronics of the neural interface devices. When developing such inductive links, the design of the implant coil is always an important issue prior to the fabrication, since there are too many factors affecting the performance of the coils, such as coil geometry and materials. Thus, it is needed to predict the coils' electrical properties and their corresponding performance in power transmission prior to the fabrication.

Considering the dimension of UEAs, power coils will have 5 mm in diameter. The other geometrical parameters should be determined to maximize the Q-factor of the coils. By applying the modeling and simulation methods proposed in this study, not only the primary parameters of inductance and series resistance, but also high frequency effects such as skin and proximity effects as well as parasitic capacitances were investigated. The power transmission performance of such coils was also predicted. Based on the simulated results, guidelines to determine optimized coil designs are suggested.

Figure 1 shows the concept of power coils that will be integrated in wireless neural interfaces. The coils are fabricated by thin film technologies based on polymer film [2]. One is a single layer thin film coil and the other is a double layer coil. For both concepts, a ferrite platelet will be used to increase the Q-factor of coils and to protect the underneath electronics against electromagnetic interferences.

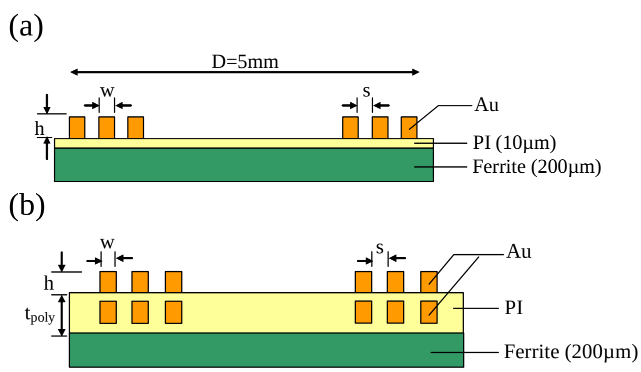

Figure 1. Design concept of integrated power module employing thin film coils: (a) single layer and (b) double layer coil mounted on a ferrite platelet.

2 MODELING AND SIMULATION METHODS

The electrical properties of thin film coils including all high-frequency effects were characterized through electromagnetic field simulations based on finite element analysis methods, using appropriate modeling of coils. The used finite element solver was FlexPDE (version 2.22a, PDE Solutions, Antioch, CA, USA). All the characteristics were simulated at a frequency of 2.64 MHz, which was selected as an operating frequency of the system envisaged.

2.1 Inductance and series resistance

A planar circular coil was modeled as a set of separated complete loops of different radii (see Figure 2, left). The length of the connecting path of two neighboring loops is much smaller than that of the loop itself so that the influence of the connecting path is negligible. To obtain the inductance and series resistance of a coil at an operating frequency, quasi-stationary electromagnetic field was analyzed for the axi-symmetric model in the region as shown in Figure 2 (right) [1].

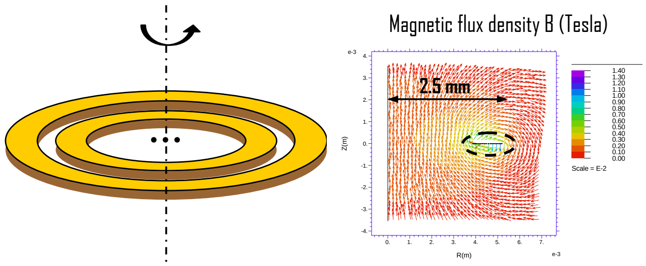

Figure 2. Modeling of circular thin film coils (left) and simulated electromagnetic field (right).

2.2 Parasitic capacitances

To predict the parasitic capacitances existing around coil windings, the electrostatic field distribution was simulated in a 2-dimensional region (Figure 3, left), and the capacitance of a coil was extracted by multiplying the 2-dimensional unit-length capacitance by the mean perimeter of the coil [1]. If conductive materials such as a silicon IC are near to the coil, the capacitance existing between coil turns and the conducting substrate should also be considered (Figure 3, right), which is easily conceivable with integrated neural interfaces. Figure 4 shows the simulated electric field around coil windings with and without a conductive substrate underneath. The capacitance between the windings and the substrate is usually much greater than the inter-winding capacitance.

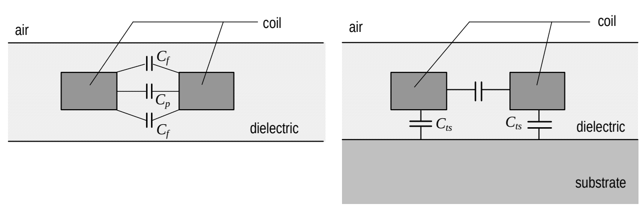

Figure 3. Parasitic capacitance between coil turns embedded in polyimide film (left) and capacitance between coil turns and the conductive substrate (right).

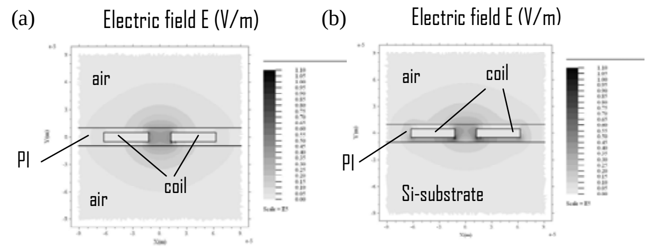

Figure 4. Simulated electric field around the coil turns (a) without and (b) with a conductive substrate underneath.

3 SIMULATION RESULTS AND DISCUSSION

Applying the proposed simulation methods, inductance and Q-factor of coils were predicted for single layer and double layer coils, according to the geometrical parameters. Figure 5 shows the inductance and Q-factor of thin film coils when the line width/spacing is fixed and the number of turns is increased, decreasing the opened area inside the coil. Q is its maximum when the windings fill the coil diameter by about 80 % of diameter toward the center. On the other hand, the inductance increases as the number of windings increases. Roughly, two-layer coils increase the inductance by a factor of 4 and the quality factor by 2, compared to those of single-layer coils.

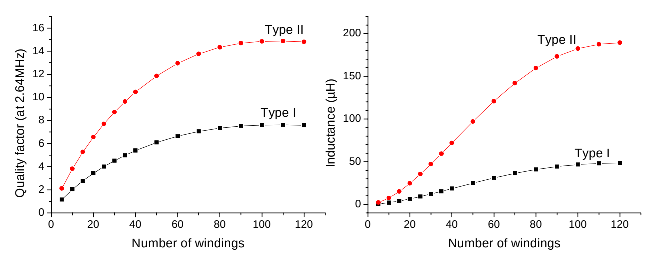

Figure 5. Q-factor and inductance of single layer (type I) and double layer coil (type II). The line width and spacing are 10 μm and the height is 20 μm.

Next, the influence of the line width was simulated with a fixed inner diameter of the coil. The inner diameter was fixed as 1.25 mm, which represents that the windings fill the coil diameter by 75 %. Figure 6 shows the inductance and Q-factor when the line width varies according to the number of windings, keeping the line spacing constant at 10 μm. As the number of windings increases, the line width decreases. When N=94, the line width is 10 μm, which was considered as a minimum width that will be fabricated.

As the number of windings increases (the line width decreases), the inductance increases and the Q-factor decreases. When the width of windings lies between 10 μm and 20 μm, an inductance of 20 to 45 μH and a quality factor Q of 10 to 7.5 can be obtained for single layer coils, and for double-layer coils L lies between 77 µH and 177 µH whereas Q reaches values from 20 to 15.

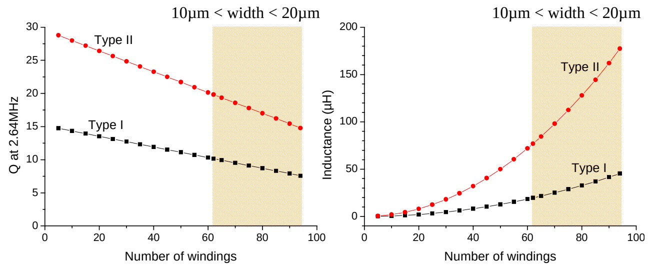

Figure 6. Q-factor and inductance of single layer (type I) and double layer coil (type II). For both coils, windings fill the diameter by 75 % to the center. The line spacing and the coil height are fixed at 10 µm and 20 µm, respectively. The shadowed region represents the actual coil width that will be fabricated.

The influence of the coil height on the coil characteristics was simulated for two different single layer coils of D_{out}=5 mm, D_{in}=1.25 mm, s=10 µm (spacing), w=10 µm (width), N=94 (number of windings) and D_{out}=5 mm, D_{in}=1.25 mm, s=10 µm, w=20 µm, N=62. The simulation results are shown in Figure 7. While the change in coil height from 10 µm to 20 µm does not affect the inductance significantly, the Q-factor is increased proportionally with the coil height.

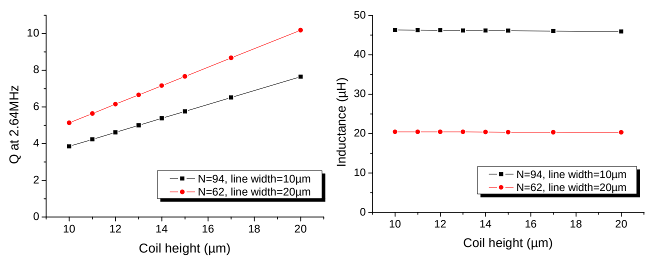

Figure 7. Q-factor and inductance of two different coil types. For both coils, windings fill the diameter by 75 % to the center and the line spacing is 10 µm.

The influence of the distance between coil layer and ferrite substrate on the coil performance was simulated. The increase of inductance due to the ferrite substrate was simulated (s. Figure 8), as a function of the distance between coil and ferrite, by comparing it to the inductance when no ferrite was used. With μ_r=200, the inductance increase is 80 % when the distance is 10 µm, and 64 % with a distance of 100 µm.

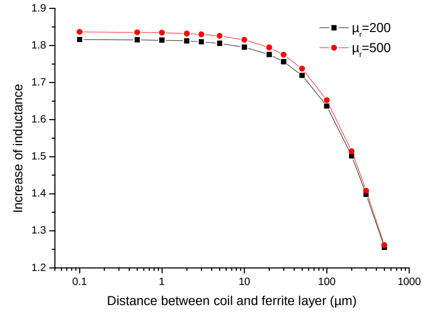

Figure 8 Influence of the distance between coil layer and ferrite substrate on the coil inductance. The coil configuration used was a single layer coil having D_{out}=5 mm, D_{in}=1.25 mm, h=20 µm, w=20 µm, s=10 µm, and N=62, resulting in L=20 µH and Q=10.

Finally, the capacitance existing between coil windings was predicted by simulation of electric fields. The result is shown in the left of Figure 9. The simulation shows that the inter-winding capacitance of such thin-film coils will be less than 1 pF. For example, a single-layer coil having h=20 µm, w=20 µm, s=10 µm, N=62 has an inductance of 20 µH and a capacitance of 0.15 pF, and this results in a self-resonance at around 90 MHz. When a conductive substrate is located under the coil, for example, a silicon IC layer, there also exists a capacitive effect between coil and this substrate. This capacitance is usually much larger than the capacitance between windings (see Figure 9). When a conducting layer, e.g. IC chip is located sufficiently apart from the receiving coil, for example, by a thick ferrite layer placed between them, the parasitic capacitance existing between coil layer and IC chip may be a few tens of pF.

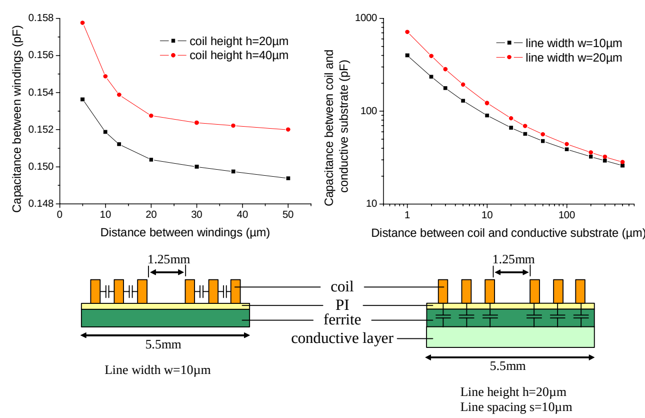

Figure 9. Capacitance between coil windings (left) and the capacitance between coil layer and a conductive substrate (right).

The performance in power transmission of such thin film coils were predicted through circuit simulations using a circuit simulator PSpice. The electrical properties such as inductance and series resistance were modeled as lumped circuit elements of inductor and resistance connected in series. This coil is magnetically coupled with a transmitter coil. The transmitter coil used for the simulation had a diameter of 2.2 cm and 17 windings made from 0.66 mm-diameter wire. The inductance of this coil was 6.03 µH and a series resistance was 0.074 ohm. The coupling between the transmitting and receiving coils was predicted through simulations to have a value of about 0.012.

The electrical properties and power transmission performance of two types of coils are listed in Table 1. To see the coil performance, the voltage gain (the ratio of the voltage obtained at the load to the voltage over the transmitting coil when a tuning capacitance is used) were calculated.

Table 1: Electrical properties and power transmission performance of two coil types. The outer diameter is D_{out}=5 mm, the inner diameter D_{in}=1.25 mm, and the coil thickness h=10 µm. The line width and spacing have the same value of 20 µm, 15 µm and 10 µm and the corresponding number of windings is N=47, 63, and 94.

	Type I (single-layer)			Type II (double-layer)		
s (=w)	20µm	15µm	10µm	20µm	15µm	10µm
L (µH)	12	20	46	45	80	180
R (ohm)	63	112	251	126	224	502
Q at 2.64 MHz	3.0	3.0	3.0	5.9	5.9	5.9
Parasitic capacitance (pF)	0.13	0.12	0.12	13.2	13.9	14.6
Self-resonance (MHz)	127	103	68	6.5	4.8	3.1
Voltage gain	0.051	0.066	0.099	0.18	0.24	0.33

In Table 2, the influence of the variation in coil height on the coil performance is summarized. The increase in coil height increases the Q-factor of the coil and as a consequence, increases the voltage gain. As shown in the table, a coil with 20 µm height would provide twice the voltage gain that could be obtained with a coil having 10 µm height when a tuning capacitance is used.

Table 2: Electrical properties and power transmission performance of a coil according to the height variation. The used coil configuration was a single-layer coil with D_{out}=5 mm, D_{in}=1.25 mm, w=15µm, s=15 µm, and N=60.

	Coil height		
	h=10 µm	H=15 µm	h=20 µm
L (µH)	19.9	19.8	19.8
R (ohm)	110	73	55
Q at 2.64 MHz	3.0	4.5	6.0
Parasitic capacitance (pF)	0.13	0.13	0.13
Self-resonance (MHz)	99	99	99
Voltage gain	0.066	0097	0.13

4 CONCLUSION

The FEA characterization method proposed in this study enables to predict the electrical properties of micro-fabricated coils to power neural interfacing devices, with all the high frequency effects like skin and proximity effects as well as parasitic capacitances. Based on the simulated results, several optimized coil designs will be fabricated and the simulation methods will be evaluated by comparing the simulation results with measurements of fabricated coils. With this simulation method, it is also possible to predict the influence of surrounding medium of coils that will be implanted in the body, e.g. biological tissue and packaging materials.

REFERENCES

[1] F. Solzbacher, R. Harrison. R.A. Normann, L. Rieth, S. Chakravarty, J.-M. Hsu, M. Klein, H. Oppermann, M. Toepper, and R. Hahn, "A next generation chronically implantable wireless neural interface," NIH/NINDS Annual Neural Interfaces Workshop, Bethesda, MD, 2005.

[2] S. Kim, K. Buschick, K. Zoschke, M. Klein, M. Toepper, D. Black, R. Harrison, P. Tathireddy, F. Solzbacher, "Polymer based thin film coils as a power module of wireless neural interfaces," submitted to IEEE Workshop on Microelectronics and Electron Devices, Boise, ID, April 14, 2006.

[3] S. Kim, O. Scholz, "FEA-characterization and optimization of planar microcoils used in implantable telemetry systems," submitted to IEEE Transactions on Biomedical Engineering.