Modeling Efficient Inductive Power Transfer Required To Supply Implantable Devices

Mohamed Sehil, Mohamad Sawan, Abdelhakim Khouas

Polystim Neurotechnologies Laboratory, Department of Electrical Engineering
École Polytechnique de Montréal, Montréal (Québec) Canada
mohamed.sehil@polymtl.ca

Abstract

This paper presents a model for inductively coupled links with an integrated receiver on silicon. To be accurate, this model includes losses related to the integration of the receiver. The modelling technique of the receiver coil has been verified using Agilent Momentum Electro-Magnetic simulations. This comprehensive model is employed to obtain maximum power efficiency by performing a discrete optimization of the geometric dimensions of the link coils. The optimized link can deliver 50mW to a visual cortical stimulator and monitoring devices with an efficiency of 21% at a distance of 1cm. The receiver has 4mm of diameter.

1. INTRODUCTION

Miniaturisation and long term use of implanted electronic systems for medical applications have resulted in a growing need of highly efficient methods for energy and data transfer. Among the existing techniques dedicated for implantable electronic devices, inductive links remain the most popular solution to wirelessly send power and data from an external transmitter to implantable biomedical devices such as visual prosthesis [1].

In biomedical applications, an inductively coupled link should have high power efficiency since it is desirable for the transmitters to be powered from lightweight battery.

Integrated spiral inductor on silicon is one of the more complicated passive components with respect to control and prediction of parasitic effects and behaviour. This kind of inductor is necessary to incorporate the receiver to the implant. Moreover, designers have traditionally determined a set of design issues for the enhancement of coupling factor through geometric approach [2] or finite element analysis [3]. The coupling factor can be enhanced if the turns of the coils are distributed across the radii. However, this distribution does not guarantee optimal power efficiency due to unloaded quality factor degradation.

Because successful design of wireless devices relies on accurate characterization of the electrical behaviour of every part of the system especially integrated spiral inductor, the lack of an accurate model for inductive links with an integrated receiver is one of the challenging problems for RF designers. In this paper we present a new methodology for efficiency enhancement of inductively coupled links. Initially, the system's behaviour can be very well predicted by establishing a model applicable to any geometrical combination. In order to avoid studying the effect of every dimension parameter on coupling and quality factors of the link coils, we propose to combine an accurate modeling and discrete optimization of geometric parameters of the link, so that we can find the optimal set of spirals providing the maximum power efficiency. The proposed model allows us to obtain optimal system efficiency for a set of coils with the smallest possible area.

2. METHODS

2.1. Receiver Modelling

Due to the large number of parameters involved (conductor width W, conductor spacing S, number of turns N, internal and outer radius, etc), the characterization and optimization of the receiver and of the whole system becomes quite complex. This is because all geometrical parameters are inter-related and different combinations may lead to the same inductance value but with different quality factors and then to different power efficiency factors.

To take into account for losses in metal, oxide and silicon layers the integrated inductor is modeled using the lumped physical model circuit, presented in figure 1 as described in [4]. The inductance and resistance of the spiral are represented by the inductance, (L_R), and the series resistance, (R_R), respectively. (C_P) represents the capacitive coupling between equiplanar conductors on top of the multilayer structure.

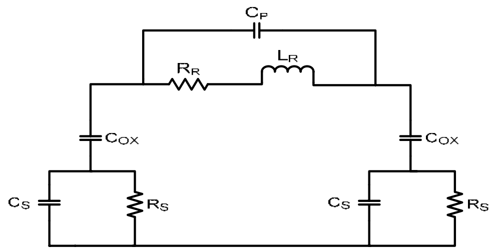

Figure 1: The lumped physical model of a spiral inductor on silicon [4]

The oxide capacitance between spiral and silicon substrate is modeled by C_{OX}. The capacitance and resistance of silicon substrate are modeled by C_{SI} and R_{SI} respectively. C_{OX}, C_{SI} and R_{SI} are calculated using formulas presented in [4]. The total inductance L_R, capacitive coupling between turns C_P and resistive losses in metal layer R_R are calculated as described in [5].

2.2. Inductive Link Modelling

A model of the inductive link has been proposed in [6], which is suitable for the case of discrete receiver coil. To accurately model the link, we incorporate the lumped physical model of the receiver spiral inductor described above in the conventional electrical model. The new electrical circuit is presented in figure 2. In this circuit, the tanks formed by (L_T,C_T) and (L_R,C_R) are tuned to resonate at the frequency of the voltage source (13.56MHz). R_opti is the load resistance determined to obtain maximum power transfer.

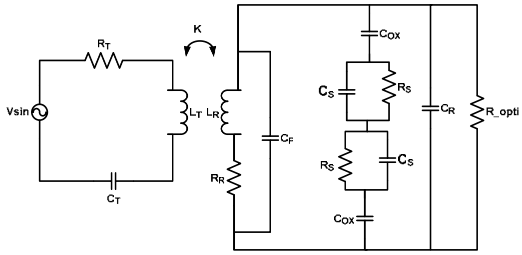

Figure 2: Electrical model used to calculate power efficiency

The transmitter spiral inductor L_T is calculated using formulas presented in [2]. The resistive losses R_T due to skin-effect in a cylindrical conductor are determined using well known techniques. Coupling factor K between coils is determined using equation (1).

$$K = \frac{M}{L_T L_R} \qquad (1)$$

Where M is the mutual inductance and is determined using formulas presented in [2].

In order to maximize the power efficiency η of the circuit of figure 2, the $\frac{d\eta}{d(Rload)}$ should equal zero. In such conditions, the corresponding optimal load resistance can be expressed by:

$$R\_opti = \frac{{Q_R}^2 R_R}{\sqrt{1 + K^2 Q_T Q_R}} \qquad (2.a)$$

Where Q_R and Q_T are the quality factors of the receiver and the transmitter respectively:

$$Q_R = \frac{\mathrm{Im}(Z)}{\mathrm{Re}(Z)} \qquad (2.b)$$

and

$$Q_T = \frac{\omega L_T}{R_T} \qquad (2.c)$$

The set of chosen coils should have an optimal maximum power transfer and R_opti almost equalizes the AC load seen by the link.

3. RESULTS

The inductive link designed should deliver a maximum of 50mW to the visual implant presented in [1], at a DC voltage of 3.3V and separation distance of 1cm. Using the modelling technique described above and a discrete optimization of the different geometric dimensions of the two coils reveals that a transmitter with 4 turns, 4.5cm in diameter and with spacing of 2mm between conductors will have a 1µH. Minimum value of spacing has been set to 2mm during optimization to facilitate manual fabrication process, increase inductance value and consequently the quality factor and the power efficiency.

Several simulations have been done to reduce external coil's outer diameter (OD), e.g for OD(cm)=(2.5;4.5;6.5) the power efficiency η(%)=(15.53;21.22;21.66) ,respectively. So, it can be deduced that for a coil having an outer diameter superior to 4.5cm, the power efficiency enhancement is not worth the area increase. The integrated receiver, fabricated from electroplated cooper, has an outer diameter of 4mm, 7 turns of 100µm of track-width, 20µm of metal thickness and has a proper inductance of 0.25µH. Chosen value for track width is a compromise between increasing number of turns to enhance coupling and reducing resistive losses. For metal thickness superior to 20µm, the decrease of resistive losses in the receiver is insignificant at the working frequency. Simulations and extraction of S parameters of the planar circular inductors were done using Agilent Momentum Electro-Magnetic Simulations (E.M) and converted to Z (inductor's impedance). Comparison between the results obtained from E.M simulations and receiver model used shows good agreement as shown in figure3.

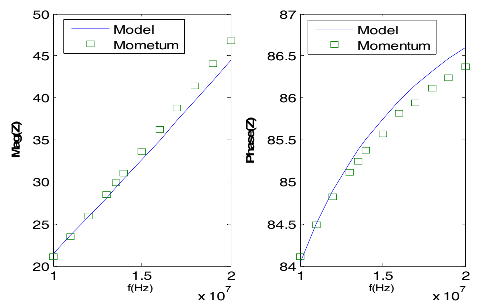

Figure 3: Magnitude and phase of inductor's Impedance

With geometric dimensions, there is also the load which affects the efficiency and delivered power. From equation (2.a), it is possible to determine the optimal load resistance for the geometric shapes of the two coils such as to provide the maximum power efficiency and necessary power to the implant (160 ohms in our case when delivering a 50mW) as seen in figure4.

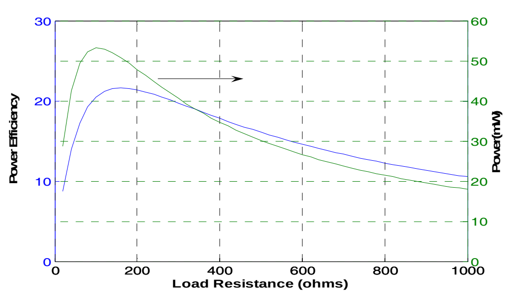

Figure 4: Power and transfer efficiency as a function of load resistance

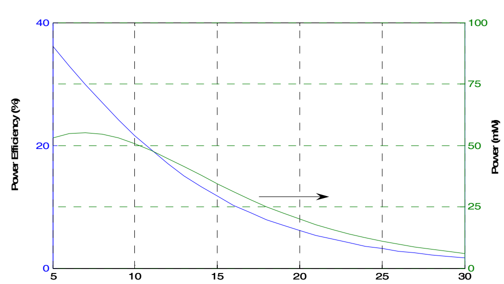

Figure 5: Power and transfer efficiency as a function of distance using optimal Load

Coupling between the two coils varies also with separation distance between the transmitter and the receiver, so do efficiency and delivered power as shown in figure5. Thus, the inductive link can deliver the required power (50mW) for the load at the expected separation distance (1cm) with a power efficiency of 21%.

4. DISCUSSION AND CONCLUSIONS

An improved model of an inductively coupled link has been developed which accounts for the losses due to the micro-fabricated receiver. Characterization of coils has been validated through the use of finite element analysis. Coupling factor predicted with equation (1) and data from literature [2]-[3], are in very good agreement. By combining the model and a discrete optimization of the different geometric dimensions we can avoid studying the effect of every dimension parameter on the coupling and quality factors of the coils and guarantee optimal power transfer. An inductive link capable to deliver a 50mW with a maximum power efficiency of 21.22% at a separation distance of 1cm was obtained. Fabrication of the micro-receiver and testing of the whole system are being undertaken.

References

[1] M. Sawan, "Wireless smart implants dedicated to multichannel monitoring and microstimulation," Pervasive Services, 2004. ICPS 2004. Proceedings. The IEEE/ACS International Conference, 19-23 July 2004. pp.21 – 26.

[2] C. M. Zierhofer, "Geometric approach for coupling enhancement of magnetically coupled coils," IEEE Trans. Biomed. Eng., vol. 43, pp.708–714, July 1996.

[3] C. Fernandez, O. Garcia, R. Prieto, J.A. Cobos, S. Gabriels, G. Van Der Borght, "Design Issues of a Core-less Transformer for a Contact-less Application," IEEE Applied Power Electronics Conference (APEC) Dallas (EEUU), march 2002

[4] C. Patrick Yue and S. Simon Wong, "Physical Modeling of Spiral Inductors on Silicon." March 2000, IEEE Transaction on Electron Devices, vol. 47, no. 3, pp. 560 – 568.

[5] P. Pieters and E. Beyne, "Spiral inductors integrated in MCM-D technology using the design space concept," in Proc. 1998 Int. Conf. Multichip Modules and High Density Packaging, pp. 478-483.

[6] W. H. Ko, Liang, S. P., Fung, C. D., "Design of radiofrequency powered coils for implant instruments" Med. &Biol. Eng. & Comput., vol. 15, pp. 634-640, 1977.

Acknowledgements

The authors would like to acknowledge the NSERC for the financial support, the CMC and ReSMiQ for the design facilities.