Wireless Power Transfer Using Resonant Inductive Coupling for 3D Integrated ICs

Sangwook Han, and David D. Wentzloff
Electrical Engineering and Computer Science Department
The University of Michigan, Ann Arbor
{swhanpns, wentzlof}@umich.edu

***Abstract*- In this paper we introduce a wireless power transfer scheme using resonant inductive coupling for 3DICs to enhance power transfer efficiency and power transfer density with smaller coils. Numerical analysis and optimal conditions are presented for both power transfer efficiency and density. HFSS simulation results are shown to verify the theoretical results. Coils for the power link are designed using a Chartered 0.13µm CMOS process. The peak power transfer efficiency is 52% and power transfer density is 49mW/mm^2.**

I. Introduction

3D integration is a promising solution for shortening interconnect in parallel processing in order to achieve smaller form-factor and higher performance. Several wired and wireless methods have been proposed to implement data communication among vertically stacked ICs in a package [1,2]. However, only wired methods such as wire-bonding or micro-bumps have been used for the power supply, even though wireless power delivery has unique advantages in 3DIC applications. It can eliminate the Known-Good-Die (KGD) issues to improve the yield, and some MEMS applications require non-contact power transfer [3], which can be realized by wireless power transfer. Fig. 1 illustrates two examples of systems requiring wireless power transfer.

Previous work has reported wireless power transmission between two inductively coupled coils in stacked dies within a package [4]. This uses standard inductive coupling which results in relatively low power efficiency (<30%) and large coils (700x700µm) since most of flux is not linked between the coils. The resonance of an inductively coupled system increases the amount of magnetic flux linked between coils and improves the power transmission significantly [5]. In this paper, we will introduce wireless power transfer using resonant inductive coupling for 3DICs to increase power transfer efficiency and density with smaller coils.

The paper is organized as follows; In Section II, we will discuss power transfer efficiency. The optimal condition and numerical analysis on maximum power transfer efficiency will be introduced. Section III discusses power transfer density. In IC designs, silicon area is always a major concern. Therefore, power density is sometimes more critical than power efficiency inside a package. We will discuss the optimal values for coil size, load resistance, and coupling coefficient k for maximum power transfer density. Section IV will show the coil design for an inductive power link and the simulation results of power efficiency and density. Section V concludes the paper.

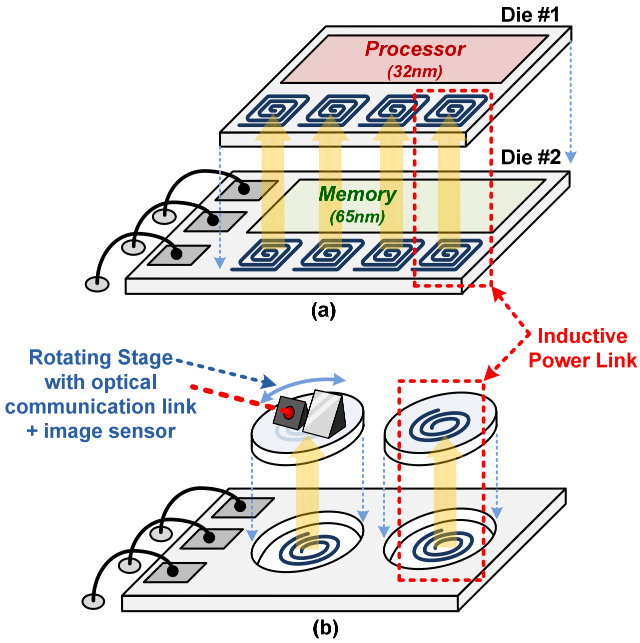

Fig. 1. The applications of wireless power transfer using inductive coupling: (a) Vertical stacking of heterogeneous processes such as logic and DRAM (b) Information Tethered Micro Automated Rotary Stages (ITMARS). Sensors and communication link are integrated on a rotating stage in a substrate.

II. Power Transfer efficiency

A. Equivalent Circuit

Fig. 2 shows the concept of an inductive power link and its equivalent circuit. The RF input signal with a power amplifier in the transmitter is modeled as a voltage source in the primary resonator. The receiver is modeled as a resister R_L in the secondary resonator. k is the transformer coupling coefficient, and L_1 and L_2 are self-inductance in transmitter and receiver coils, respectively. R_1 and R_2 model the losses in the coils. C_1 and C_2 are capacitors including parasitic and external capacitance to create a resonance at the transmitter and receiver side. Standard inductive coupling uses a frequency well below the self-resonant frequency of the inductors, therefore parasitic

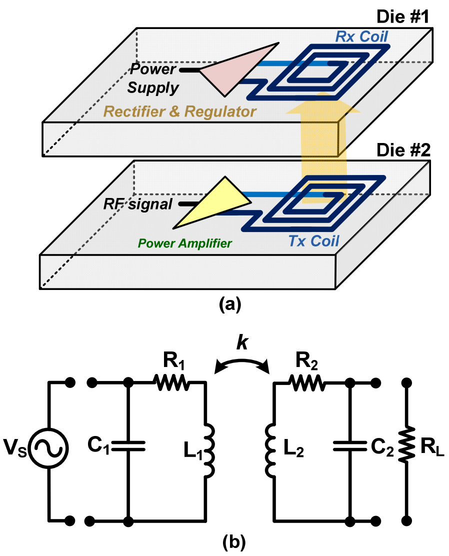

Fig. 2. (a) Concept of wireless inductive power link (b) Equivalent circuit

capacitance (C_1, C_2) are typically ignored in this case. Resonant inductive coupling, however, uses this capacitance to resonate with the inductors, increasing the flux linked between transmitter and receiver.

B. Analysis with Equivalent Circuit

As shown in Fig. 3 (a), the circuit with a transformer can be converted to the equivalent circuit with the reflected load *Ze*. *Ze* captures the impact of the secondary part on the primary part. The reflected impedance *Ze* can be expressed by

$$Z_e = \frac{S^2M^2}{Z_2} = \frac{R_{p2}k^2Q_1Q_2{}' + sMk^2Q_1Q_2{}'}{{}^{R_{p2}}/_{R_1} + k^2Q_1Q_2{}'} \quad (1)$$

where $Q_2{}' = \omega L_2/R_{p2} = \omega L_2/(R_L \| Q_2{}^2 R_2)$. The power consumed at *Ze* should be identical to the power transferred to the secondary part. Considering that the real part of (1) is the resistive component, we can derive the fraction of delivered power to secondary part at resonance. This is the power efficiency at the primary side, η_1.

$$\eta_1 = \frac{re(Z_e)}{R_1 + re(Z_e)} = \frac{k^2Q_1Q_2{}'}{1 + k^2Q_1Q_2{}'\left(1 + {}^{R_1}/_{R_{p2}}\right)} \quad (2)$$

At the secondary equivalent circuit, shown in Fig. 3 (b), the parasitic resistance can be converted into an equivalent parallel loss across the LC tank. The power from the primary part will be dissipated in both R_2 and R_L, and the power consumed at R_L represents the net output power available at the receiver. At resonance, the power efficiency at the secondary part, η_2 can be written as

$$\eta_2 = \frac{Q_2{}^2R_2}{Q_2{}^2R_2 + R_L} = \frac{Q_2}{Q_2 + Q_L} \quad (3)$$

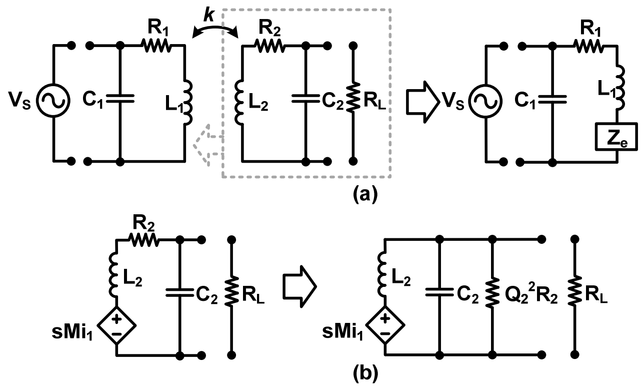

Fig. 3. (a) Entire equivalent circuit (b) Secondary equivalent circuit

Combining (2) and (3), the total power efficiency of the inductive power link is derived as a form similar to [6-8].

$$\eta = \eta_1\eta_2 = \frac{k^2Q_1Q_2{}'}{1 + k^2Q_1Q_2{}'\left(1 + {}^{R_1}/_{R_{p2}}\right)} \cdot \frac{Q_2}{Q_2 + Q_L} \quad (4)$$

C. Maximum Power Transfer Efficiency

The power transfer efficiency can be maximized by adjusting conditions such as *R*, *L*, *C* of coils and R_L value. In practice, for planar integrated spiral inductors it is difficult to adjust the *L*, *C*, and *R* values of the coils independently, since all the values are partially correlated. Therefore, R_L is the best practical factor to adjust when optimizing the wireless link for a given coil. By differentiating (4) w.r.t. R_L, the optimal R_L can be obtained as

$$R_{L\,opt} = \frac{Q_2R_2}{k} \quad (5)$$

This optimal condition makes the maximum power transfer efficiency a function of coupling coefficient *k* and quality factor of the coils, both of which may be optimized when designing the coils.

$$\eta_{Max} = \frac{k^2Q_1Q_2}{(kQ_1 + k^2 + 1)(kQ_2 + 1)} \quad (6)$$

With large values of *k* and *Q*, the power efficiency approaches 1 as expected.

III. Power Transfer Density

While high power transfer efficiency is critical for low power systems, area-constrained systems can require larger power transfer through smaller area coils at an acceptable loss in efficiency. With a fixed distance between two coils, larger coils result in larger *k* and higher efficiency. However, using larger coils requires more silicon area, and it ultimately decreases the power transfer density. Therefore, a parallel power transfer scheme can be taken into consideration in order to increase power density and maximize the amount of power delivery through the same area, as illustrated in Fig. 4.

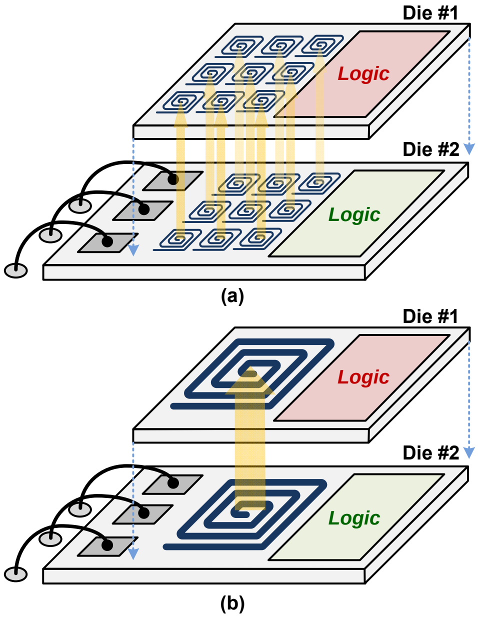

Fig. 4. Concept of parallel inductive power transfer (a) parallel power delivery using multiple maximum-power-density coils (b) single power delivery using one large coil

In order to compare the performance of single inductive power link to a parallel inductive power link, the power transfer density should be analyzed first.

A. Output Delivered Power

Fig. 5 shows that the transformer circuit has the equivalent circuit with reflected impedance and parallel resistance. The reflected impedance is split into the imaginary and real part, and the real resistive part is converted to parallel resistance using quality factor $Q_p = \omega L_1/(R_1 + re(Z_e))$.

At resonance, the input power is given by

$$P_i = \frac{1}{2}\left(\frac{|V_S|^2}{{Q_p}^2(R_1+re(Z_e))}\right) \tag{7}$$

and the output power can be written as

$$\begin{aligned} P_o &= \eta P_i = \eta_1\eta_2 P_i \\ &= \frac{1}{2}\cdot\frac{{Q_2}^2R_2}{{Q_2}^2R_2+R_L}\cdot\frac{re(Z_e)}{R_1+re(Z_e)}\cdot\frac{|V_S|^2}{{Q_p}^2(R_1+re(Z_e))} \\ &= \frac{1}{2}\cdot\frac{{Q_2}^2R_2}{{Q_2}^2R_2+R_L}\cdot\frac{k^2|V_S|^2}{Z_2} \end{aligned} \tag{8}$$

B. Optimal Load

The power transfer also can be maximized by adjusting the R_L value. By differentiating (8) w.r.t. R_L at resonance, the optimal R_L can be expressed as

$$R_{L\,opt} = {Q_2}^2R_2(1-k^2) \tag{9}$$

Substituting the optimal R_L into (8), we get the maximum power transfer amount as

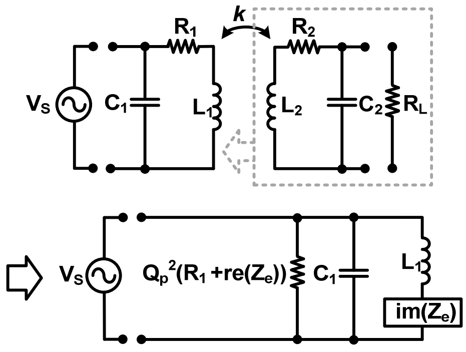

Fig. 5. Equivalent circuit for power density calculation

$$P_{o\,Max} = \frac{1}{8}\frac{k^2}{R_2(1+k^2)}|V_S|^2 \tag{10}$$

C. Power Transfer Density

The power transfer density is defined as the amount of available transferred power per the unit area. Assuming square-shaped, planar spiral coils are used with diameter d, the power transfer density will be a function of d. In addition, coupling coefficient k is also the function of d [9].

$$k = \left(\frac{d^2}{12x^2+d^2}\right)^{1.5} \tag{11}$$

where x is the distance between coils. With (11), the power transfer density is given by

$$\begin{aligned} P_{Den} &= \frac{P_{o\,Max}}{d^2} = \frac{1}{8}\frac{k^2}{d^2R_2(1+k^2)}|V_S|^2 \\ &= \frac{1}{8}\frac{|V_S|^2}{R_2}\cdot\frac{d^4}{(12x^2+d^2)^3+d^6} \end{aligned} \tag{12}$$

By differentiating (10) w.r.t. d, the optimal size of the coils and corresponding k can be found as the function of the separation between coils, x. For instance, when x=15µm, the optimal d is 58µm, and k is equal to 0.41.

IV. Simulation Results

A. Simulation Setup

To verify this model, we designed planar spiral coils using a Chartered 0.13µm CMOS process. Fig. 6 shows the simulation setup of two identical square coils vertically stacked to implement the inductive power link through stacked ICs. We sweep the separation x, and the diameter d to test power efficiency and density. HFSS is used to extract the lumped-element models for coils, and these models are imported to Sperctre to simulate the inductive power link.

B. Power Transfer Efficiency

As shown in (6), the maximum power transfer efficiency strongly depends on k. To show this dependency, we swept the

TABLE I

DETAILS OF COILS

Parameter	Value	
	Power Efficiency	Power Density
Diameter d	60µm	20~120µm
Distance x	5~30µm	15µm
Width	0.65µm	0.65~1.5µm
Space	0.35µm	0.35~2.0µm
Number of turns	5	5
Number of layers	4	4
Q	3.92	1.27~4.16
$freq_{res}$	3.75GHz	1.33~10.1GHz
k	0.432	0.046~0.773

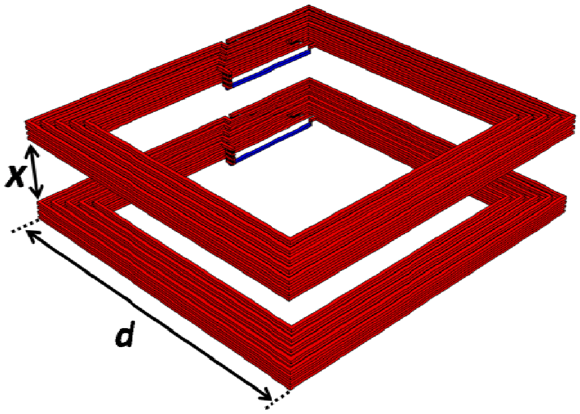

Fig. 6. Two vertically stacked coils for wireless inductive power link

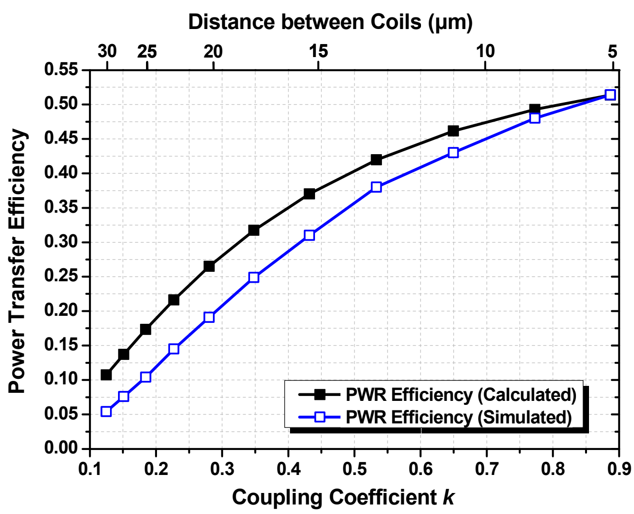

Fig. 7. Coupling coefficient k vs. power transfer efficiency

distance x from 5µm to 30µm with 60µm-sized coils. It maintains a Q-factor of 3.9 while k varies from 0.125 to 0.887. Fig. 7 shows the simulation results of the maximum power transfer efficiency when using the optimal load resistance. The simulation values match the theoretical values well. As expected, higher k results in higher power transfer efficiency. When k=0.887 (60µm coils, 5µm separation), we can achieve a power transfer efficiency of 52%.

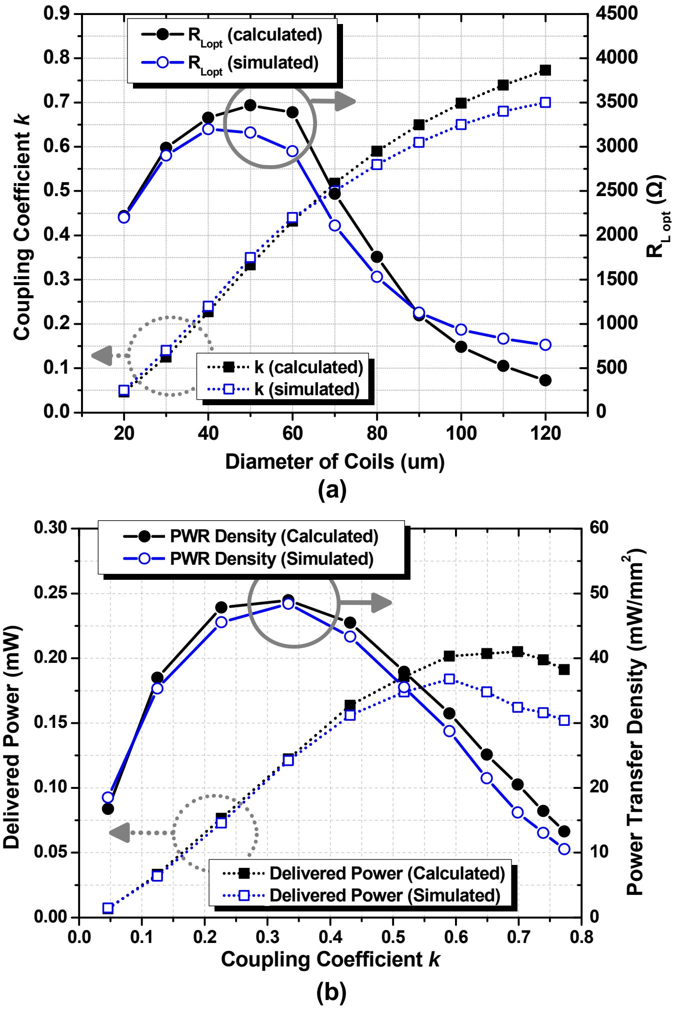

Fig. 8. (a) The coil diameter vs. coupling coefficient k and the optimal R_L (b) coupling coefficient k vs. power transfer amount and power transfer density

C. Power Transfer Density

To verify the power transfer density model, we designed 11 coupled coils which have varying diameters from 20µm to 120µm in 10µm steps. The distance between the paired coils is fixed at 15µm, which can be reasonably achieved with face-to-face stacking of two CMOS die. Over this range, k varies from 0.05 to 0.77, as shown in Fig. 8 (a). With the specific dimensions, we can calculate k and the optimal R_L by (9) and (11) respectively, and the theoretical values match the simulation results.

Fig. 8 (b) shows the maximum delivered power amount and power transfer density depending on k. As mentioned in Section III, when the separation x=15µm, the optimal coil size for the maximum power density is 58µm and k is 0.41. The simulation result verifies this; the optimal k is about 0.35 and

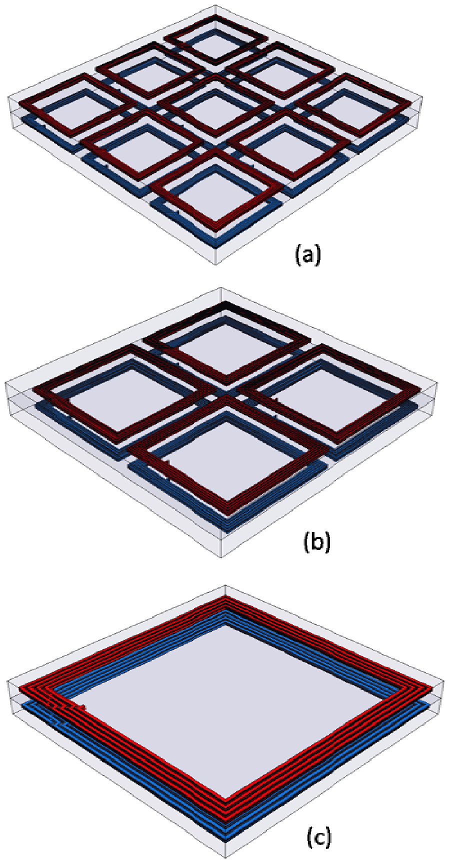

Fig. 9. Simulation setup for parallel inductive power link (a) 3x3 array of 60µm x 60µm coils (b) 2x2 array of 90µm x 90µm coils (c) single 200µm x 200µm

the optimal size is about 55µm. The maximum power transfer density is 49mW/mm^2.

D. Performance Comparison

In order to compare the performance between parallel and single inductive power links, we simulated the power efficiency and maximum power transfer for the three configurations shown in Fig. 9. Assuming the same area of 200µm x 200µm, we assigned a 3x3 array of 60µm x 60µm coils (optimal power density), a 2x2 array of 90µm x 90µm, and a single 200µm x 200µm coil (maximum power efficiency). The separation of the stacked coils is 15 µm. The results are shown in Fig. 10. Since the single 200µm x 200µm coil has the largest *k*, it has the highest power efficiency of 52%. However, the total delivered power amount becomes the largest with the 3x3 array because 60µm x 60µm coil has the highest power density. A simulated power transfer of 1.48mW was achieved over the link, which is five times larger than the single inductive power link.

V. Conclusion

The performance of a wireless inductive power link can be improved by using resonant inductive coupling. For low power

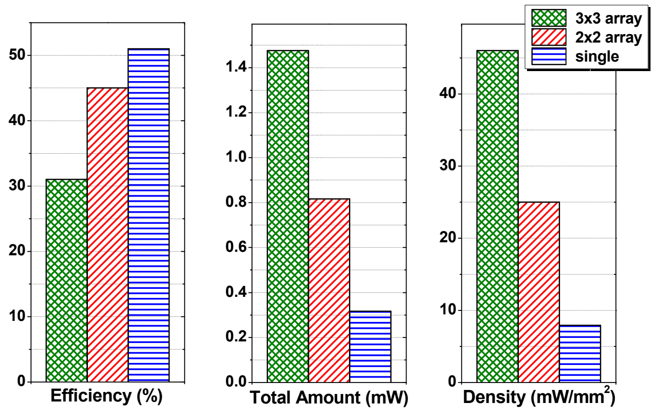

Fig. 10. Simulation results: power transfer efficiency, total delivered amount, and power transfer density of three cases

systems and high power efficiency, higher *k* and *Q* are required. However, in order to increase the absolute power transfer amount, power density is critical, and the optimal value of *k* to maximize power density depends on the distance and coil technology. Therefore, the parallel inductive power link with the optimal sized coils can deliver more power than the single inductive power link can while the latter has higher efficiency.

Acknowledgment

Sangwook Han is partially funded by a Samsung Scholarship. This work is supported by the DARPA Young Faculty Award.

References

[1] K. Niitsu, Y. Shimazaki, Y. Sugimori, Y. Kohama, K. Kasuga, I. Nonomura, M. Saen, S. Komatsu, K. Osada, N. Irie, T. Hattori, A. Hasegawa, and T. Kuroda, "An Inductive-Coupling Link for 3D Integration of a 90nm CMOS Processor and a 65nm CMOS SRAM," *ISSCC Dig. Tech. Papers,* pp. 480-481, Feb 2009.

[2] R. Cardu, M. Scandiuzzo, S. Cani, L. Perugini, E. Franchi, R. Canegallo, and R. Guerrieri, "Chip-to-Chip Communication Based on Capacitive Coupling," *IEEE Conference on 3D System Integration* 2009

[3] Information Tethered Micro Automated Rotary Stages (ITMARS), DARPR MTO BAA 08-74 [Online] http://www.darpa.mil/mto/solicitations/baa08-74/index.html

[4] K. Onizuka, H. Kawaguchi, M. Takamiya, T. Kuroda, and T. Sakura, "Chip-to-Chip Inductive Wireless Power Transmission System for SiP Applications," *IEEE CICC 2006*

[5] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Solijacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," *Science Express,* Vol. 317. no. 5834, pp. 83 - 86 July 2007

[6] W. H. Ko, S. P. Liang, and C. D. F. Fung, "Design of Radio-Frequency Powered Coils for Implant Instruments," *Med. Biol. Eng. Comput.,* Vol. 15, pp. 634-640, 1997

[7] M. W. Baker and R. Sarpeshkar, "Feedback Analysis and Design of RF Power Links for Low-Power Bionic Systems," *IEEE Trans. Biomed. Circuits Syst.* Vol.1, pp. 28-38, 2007

[8] U. Jow and M. Chovanloo, "Design and Optimization of Printed Spiral Coils for Efficient Transcutaneous Inductive Power Transmission," *IEEE Trans. Biomed. Circuits Syst.* Vol.1, pp.193-202, 2007

[9] N. Miura, D. Mizoguchi, T. Sakurai, and T. Koroda, "Analysis and Design of Inductive Coupling and Transceiver Circuit for Inductive Inter-Chip Wireless Superconnect," *IEEE Journal of Solid-State Circuits,* Vol. 40, pp.829-837, 2005