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Influence of system integration and packaging for a wireless neural interface on its wireless powering performance

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Abstract – **In an integrated wireless neural interface based on the Utah electrode array, the implanted electronics is supplied with power through inductive coupling between two coils. This inductive power link would be affected by conductive and dielectric media surrounding the implant coil. In this study, the influences of the integration of implant coil on silicon based IC/electrode, thin film parylene coating, and physiological medium surrounding the coil were investigated systematically and quantitatively. A few different versions of implant coils were made by winding fine wire with a diameter of around 50 µm. The parasitic influences affecting the inductive power link were empirically investigated by measuring the electrical properties of coils in different configurations and in different media. The distance of power transmission between the transmit and receive coils was measured when the receive coil was in air and immersed in saline solution to simulate an implanted physiological environment. The results from this study suggest factors to be considered when integrating and encapsulating implantable devices that employ inductive power link.**

I. INTRODUCTION

In a recently developed, integrated wireless neural interface based on the Utah Electrode Array (UEA), power is supplied to the implanted electronics through inductive coupling [1]-[3]. When such a neural interface is implanted in the body, the inductive power link would be affected by the conductive and dielectric properties of the materials surrounding the two coils and the media existing between them; for instance, silicon substrate underneath the implant coil when the coil is integrated with the IC and UEA [4], coating materials used for hermetic encapsulation [5]-[7] and mechanical protection of the device, and the surrounding biological medium in a physiological environment. Practically, tuning a power receive coil at a specific frequency to maximize the voltage and power reception is not quite straightforward, because the presence of conductive or dielectric media nearby the coil will affect the coil's electrical property and as a result, its performance in wireless power reception. Therefore, it is important to predict changes in electrical properties of the coil caused by device integration/encapsulation and implantation in a physiological environment, in order to achieve a maximum power transmission distance.

For the use in such neural interfaces, two different embodiments of flat spiral coils were made in a diameter of up to 5.5 mm, by winding insulated Cu- and Au-wire with a diameter of 45 µm and 56 µm, respectively. To quantitatively investigate the aforementioned influences of the media surrounding the coil on its power transmission, the electrical properties of the coils such as inductance, series resistance, and self capacitance were measured when a silicon substrate was present underneath the coil or not. The distance of power transmission between the transmit and receive coils was measured when the coil was in air and in physiological solution.

II. COIL DESIGN AND CHARACTERIZATION

A. Design of Implant Coils

In our application, an inductance of 20–30 µH was desirable for the implant coil to match the input impedance of the implant IC and to achieve a sufficient quality factor [8]. A quality factor was desired to be greater than 14, including all parasitic losses involved in the input to the IC. The outer diameter of the coil was determined to be within 5.5 mm, to be suitable for the dimension of the envisioned neural interface [9]. After a series of numerical simulations using finite element analysis (FEA) [10], optimized coil designs were derived and sample coils were made by winding microwires at IEC Company (Conway, SC). We made two types of microwire wound coils: one was made of insulated Cu-wire in a diameter of 44.7 µm and the other was made of Au-wire in a diameter of 55.9 µm. Cu-wire wound coils were intended for bench top, *in vitro* and acute *in vivo* tests of supplying the integrated neural interface, while Au-wire coils were to be integrated in the devices for chronic implantation. The design parameters used for the implant coils are listed in Table 1.

Table 1: Design parameters of two types of microwire wound coils.

	Cu-wire coil	Au-wire coil
Outer diameter	5.0 mm	5.5 mm
Inner diameter	1.3 mm	1.3 mm
Wire diameter	44.7 µm	55.9 µm
Number of turns	34 per layer	30 per layer
Coating thickness	5 µm	5 µm
Thickness	165 µm (3 layers)	200 µm (3 layers)
Electrical conductivity	5.9 x 10^7 S/m	4.5 x 10^7 S/m

B. Electrical Properties of Coils

The effects of coil integration on the IC/UEA, parylene encapsulation, and implantation in a physiological environment were investigated by measuring the impedance and resonance frequency of coils in different configurations. To

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simulate the integration of the coil on the silicon IC/UEA, coils were mounted on a silicon substrate in a size of 8.00 × 7.55 mm^2 and a thickness of 2 mm, which has the same thin film metal traces on it as the UEA does, consisting of a sputter deposited Ti/Pt/Au film in thicknesses of 50/150/150 nm, respectively [9]. Saline solution (0.9 % NaCl) in a thickness of 10 mm was used to simulate a physiological environment and the coils were completely immersed in solution. The inductance and series resistance of the Cu- and Au-wire wound coils were measured over a frequency range up to 30 MHz using a precision LCR meter (Agilent 4285A). The self resonance frequency and self capacitance of the coils were also measured and are shown in Table 2 for Cu-wire coil and Table 3 for Au-wire coil.

As shown in tables below, the silicon substrate underneath the coil (see Fig. 1) did not affect the coil's electrical properties much. On the other hand, the self capacitance was affected significantly by the presence of saline solution surrounding the coil, which increased the coil's effective capacitance by about 40 pF. This has to be taken into account when selecting a capacitance value to tune the coil at a frequency, which is the frequency of power as well as clock signal for the digital circuitry in the IC [11], [12].

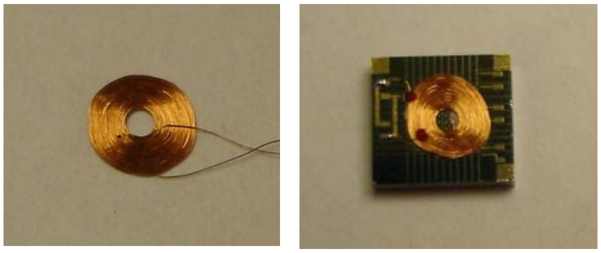

Fig. 1: Photograph of a flat 3-layer Cu-wire wound coil (left) and when it is mounted on a dummy silicon die (right).

Table 2: Electrical properties of a Cu-wire wound coil.

		No Si substrate underneath		Si substrate underneath	
		In air	In sol.	In air	In sol.
L_s (μH)	100 kHz	29.1	29.1	28.7	28.7
	2.765 MHz	29.4	49.6	29.2	38.9
R_s (Ω)	100 kHz	13.6	13.4	13.9	13.7
	2.765 MHz	16.7	192.1	26.3	75.6
f_{self} (MHz)		22	4.2	21	5.2
C_{self} (pF)		1.80	49.3	2.00	32.6

Table 3: Electrical properties of a Au-wire wound coil.

		No Si chip Underneath		Si chip Underneath	
		In air	In sol.	In air	In sol.
L_s (μH)	100 kHz	26.7	26.7	26.2	26.1
	2.765 MHz	26.9	30.3	26.5	35.7
R_s (Ω)	100 kHz	15.2	15.2	14.4	14.4
	2.765 MHz	17.9	401.7	27.2	234.4
f_{self} (MHz)		> 30	4.3	23	4.8
C_{self} (pF)		< 1.05	51.3	1.83	42.1

III. POWER TRANSMISSION

A. *Power Transmitter*

The power transmit coil used in this study was a spiral coil printed on a circuit board [11], which had a diameter of 5.8 cm and 28 turns resulting in an inductance of 21 μH and series resistance of 5.1 Ω. The power board used a class E power amplifier to create a 2.765 MHz waveform of up to 80 V_{rms} at a 10 V supply. The resulting AC magnetic field was received at the implant coil and supplied the IC connected to the coil. Techniques described in [8] were used to optimize the power link. A USB link to a laptop PC allowed the user to send command strings that modulate the amplitude of the coil voltage. The power transmitter board drew a current of 220 mA at 10 V supply, resulting in a power consumption in the entire transmitter circuitry of 2.2 W.

B. *Distance of Power Transmission*

The distance of wireless powering was measured using the wire wound coils when they were connected to the QFP packaged INI4 ('Integrated Neural Interface', version 4) chip [13] through lead wires in a length of about 4 cm for testing convenience, as shown in Fig. 2. Both Cu-wire and Au-wire coils were mounted on silicon substrate that was fabricated in the same way as the actual UEA, except that the electrodes were not diced and etched (see Fig. 1, right). The used capacitances to tune the coils at 2.765 MHz are listed in Table 4 for each configuration. The received unregulated voltage and the regulated voltage in the INI4 chip were measured using oscilloscope, as a function of coil distance. When the unregulated voltage was greater than 4.3 V, the INI4 circuitry was functioning properly, supplied with a DC voltage of greater than 3.0 V. The transmission distance was measured when the coil was in air and immersed in saline solution. Measurements were repeated three times for each configuration.

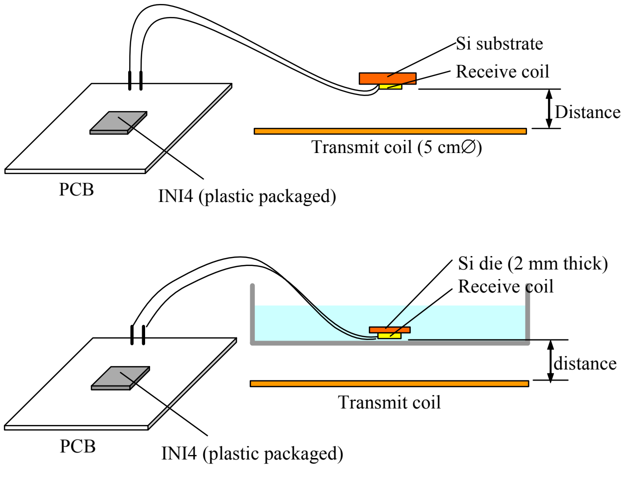

Fig. 2: Schematic of the voltage measurement setup. The received voltage was measured when the coil was in air (top) and immersed in saline solution (bottom).

Table 4: Capacitance values used to tune the coil at 2.765 MHz.

	Cu-wire coil		Au-wire coil	
	In air	In sol.	In air	In sol.
Tuning capacitance (pF)	88	52	95	52

Fig. 3 shows the wirelessly received voltage as a function of coil distance. For Cu-wire coil, when it was tuned at resonance, a regulated voltage greater than 3 V was received up to 18 mm in air and 13 mm in saline. For Au-wire coil, the transmission distance was up to 18 mm in air while it was 11 mm in saline. When the coil was immersed in solution, the quality factor of the coil decreased by about 60 %, which in turn decreased the transmission distance by an amount of around 30 %.

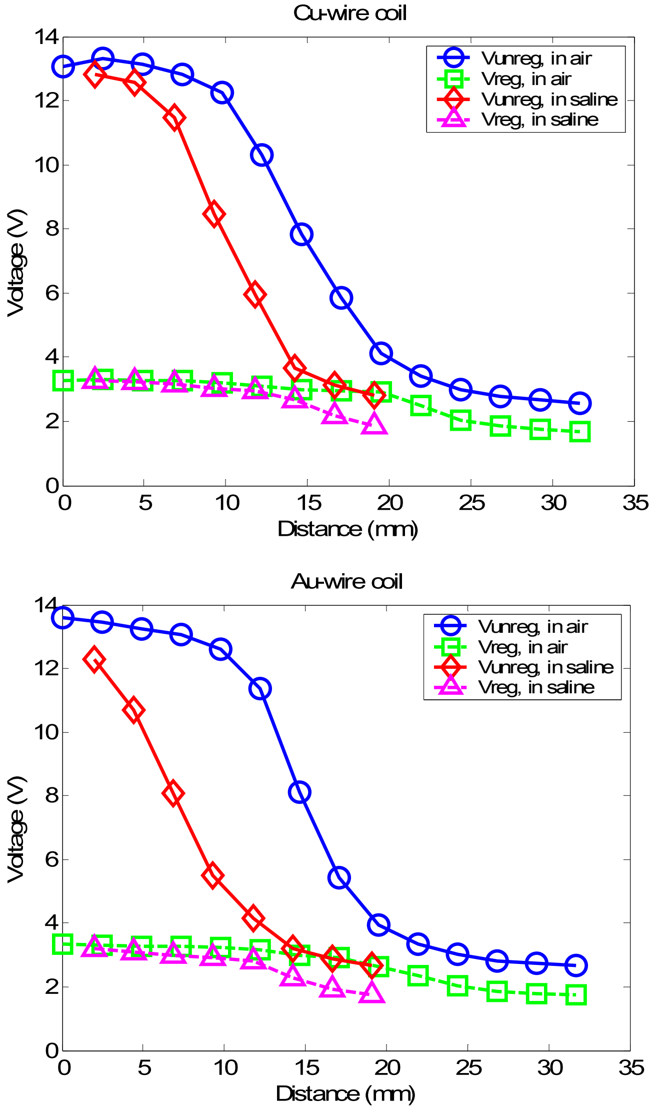

Fig. 3: Wirelessly received unregulated and regulated voltages as a function of coil distance.

IV. COIL INTEGRATED ON TOP OF INI4 CHIP

We have also tested an integrated assembly consisting of a wire wound coil mounted on a silicon substrate (to model the coil integration on the IC/array assembly [9]), which was again mounted on to a QFP packaged INI4 chip as shown in Fig. 4. A Au-wire coil was used in this test. The unregulated voltage across the smoothing capacitor was measured as a function of coil distance. Although this assembly was built based on a SMD packaged INI4, not on a bare chip as described in [9], this would help estimate the influences of coil integration on silicon substrate, parylene encapsulation, (optional) additional silicone protection layer, and immersion in a physiological solution. We were able to supply this assembly at a distance of up to 18 mm, demonstrating that the data transmitter embedded in the INI4 chip [11] could broadcast RF signals at 903 MHz, as shown in Fig. 5.

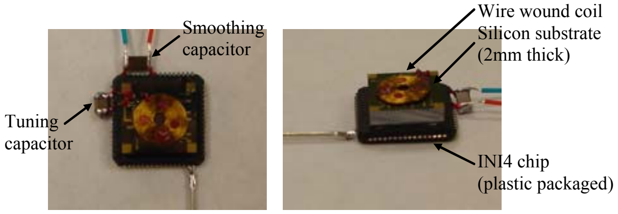

Fig. 4: An assembly of a Au-wire wound coil on a silicon substrate that was mounted on top of a packaged INI4 chip to test the wireless powering to the INI4 chip.

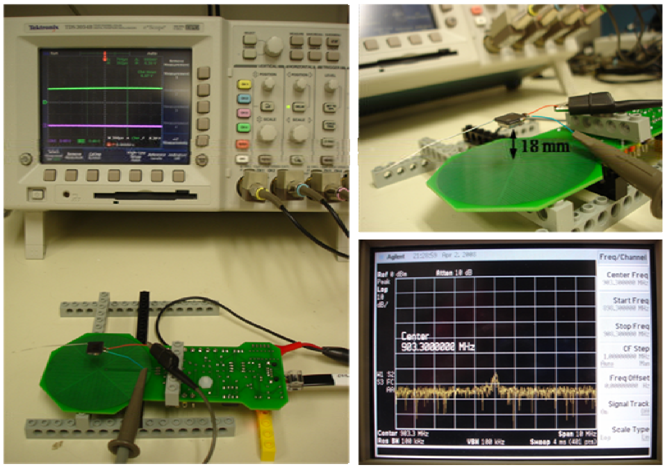

Fig. 5: Experimental setup to measure the wirelessly received voltage across the regulator input of the INI4 chip using an oscilloscope (left). The coil was suspended in air and received voltage wirelessly from the power/command transmit coil (right, top). The INI4 chip sent out RF signals around 900 MHz (right, bottom).

V. DISCUSSION AND CONCLUSIONS

In this study, the conductive and dielectric effects of the media surrounding an implant coil on the inductive power link were investigated empirically and quantitatively. The integration of the coil on the silicon based IC/UEA did not have significant influence on the electrical properties of the coil. On the other hand, when the coil was in a physiological environment, the power transmission was affected significantly resulting in a decreased transmission distance. These effects need to be taken into account when selecting a capacitance for tuning the implant coil at a desirable operation frequency.

The assembly shown in Fig. 4 will be coated with parylene C and an optional additional protection layer of medical grade silicone. The received voltage at the load and the transmission distance will be measured after parylene coating, silicone backing and immersion in saline solution. This will provide quantitative estimates on the influences of the media surrounding the coil on the performance in wireless transmission.

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