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Wireless Power Delivery for Retinal Prostheses

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***Abstract*— Delivering power to an implanted device located deep inside the body is not trivial. This problem is made more challenging if the implanted device is in constant motion. This paper describes two methods of transferring power wirelessly by means of magnetic induction coupling. In the first method, a pair of transmit and receive coils is used for power transfer over a large distance (compared to their diameter). In the second method, an intermediate pair of coils is inserted in between transmit and receive coils. Comparison between the power transfer efficiency with and without the intermediate coils shows power transfer efficiency to be 11.5 % and 8.8 %, respectively. The latter method is especially suitable for powering implanted devices in the eye due to immunity to movements of the eye and ease of surgery. Using this method, we have demonstrated wireless power delivery into an animal eye.**

I. Introduction

Many implanted prostheses require electrical power to function; be it in the form of an implanted battery or via wireless power transmission. It is often advantageous to develop methods for wireless power transmission to an implant located deep inside the body as replacement of batteries which requires additional surgery is undesirable. An example of this is a retinal prosthesis. A retinal prosthesis can create a sense of vision by electrically stimulating intact neural cells in the visual system of the blind [1], [2]. Such prostheses will require continuous power transmission in order to achieve real-time moving images. Efficient transmission of power is a performance-limiting factor for successful implementation the prosthesis. We estimate that a high density electrode array with more than 1000 electrodes will consume about 45 mW of power. This includes 25 mW to operate the electronics on the chip and an additional 20 mW for neuronal stimulation with a 3.3 V stimulation threshold. The latter is calculated based on 64 simultaneously operating electrodes each requiring a maximum of 0.3 mW at 60 Hz image refresh rate.

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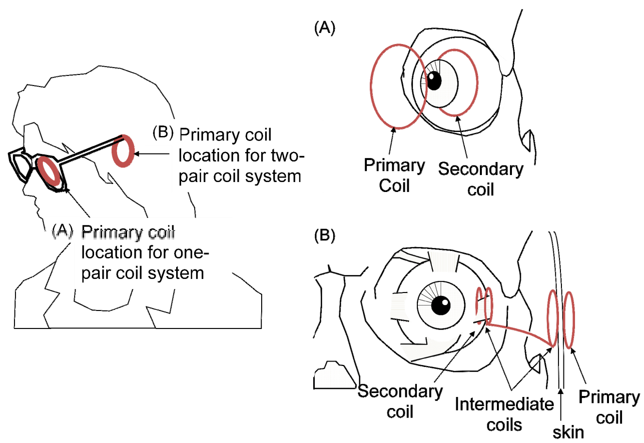

Fig. 1. Drawings showing location of possible coil locations and configuration on the head and eye for; (A) one-pair and (B) two-pair coils.

The supply of power to the retinal prosthesis is difficult due to many factors. Apart from the need to deliver power wirelessly to eliminate the risk of infection through exposed tethers, constant motion of the implant results in variation in the wireless system operating conditions. Furthermore, electrode-tissue impedance which acts as load for electrical stimulation is likely to change over time from initial implantation due to tissue growth over the implanted prosthesis.

Inductive coupling of magnetic field is an efficient way for transmitting energy through tissue [3]-[5]. This is because electrical energy can be easily converted to magnetic energy and back using conductive coils. Traditionally, a pair of inductive coils; a primary (transmit) and a secondary (receive) coils, are used. The secondary coil can be located within the eye and the primary coil external to the eye. However, several problems will arise if we implement this method. The first problem is difficulty in placing a large receive coil inside the eye. This will require complicated surgical procedure, often a major challenge in implementing a wireless power solution. The other problems we face are large separation between the coils and the constant relative motion between the primary and secondary coils. The latter problems result in reduction in power transfer to the device.

In order to overcome these problems we propose the use of an intermediate link between the primary and secondary

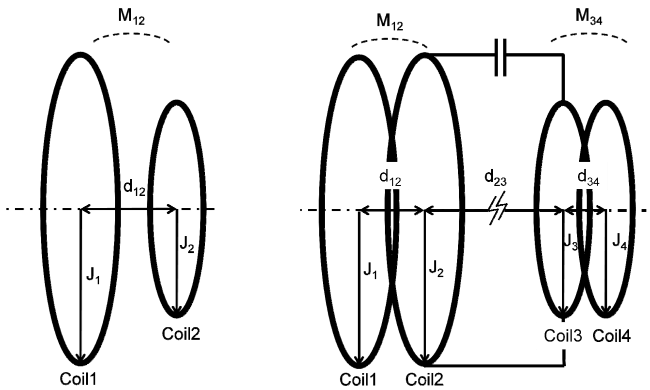

Fig. 2 Schematic showing physical configuration for one-pair and two-pair coils.

coil as shown in Fig. 1. In this figure we show the possible locations for one-pair coils and a two-pair coils system which consists of an additional intermediate link made out of a pair of serially connected coils. In this method, the secondary coil is located under the sclera (eye wall) and is connected to the implanted device via electrical wires which are embedded under the wall of the eye. By placing these components under the sclera, we avoid having a permanent wire breaching through the eye wall. The transmit coil is placed on the skin of the head at an inconspicuous location, for example at the back of the ear. The intermediate coils are positioned with one end on the sclera over the receive coil and the other end under the skin beneath the transmit coil. The advantage of this method is immunity to variation in coupling due to rapid movements of the eye as relative motion between adjacent coils is restricted. It also has the potential to increase the power transfer efficiency compared to a one-pair coils system.

In this paper we study power transfer for both systems and present our finding when the coils are implemented using spiral coils fabricated on flexible printed circuits.

II. Wireless Power Transfer Analysis

For an inductive link, power transfer efficiency is inversely proportional to the separation between the coils. That is, the power transferred across the coils is reduced when the coil separation is increased. By introducing a pair of intermediate coils in between a pair of widely separated primary and secondary coils, effectively converting the single-pair coils system to a double-pair coils system, we can potentially improve power transfer efficiency.

Figure 2 shows the schematic of one-pair and two-pair coils. The symbols J, d and M represent the radius of the coils, adjacent coil separation and mutual inductances between the coils. The single digit subscripts refer to the individual coils while the double-digit subscripts indicate the relationship between adjacent coils. The intermediate coils Coil2 and Coil3 for the two-pair system are connected using a series matching capacitor.

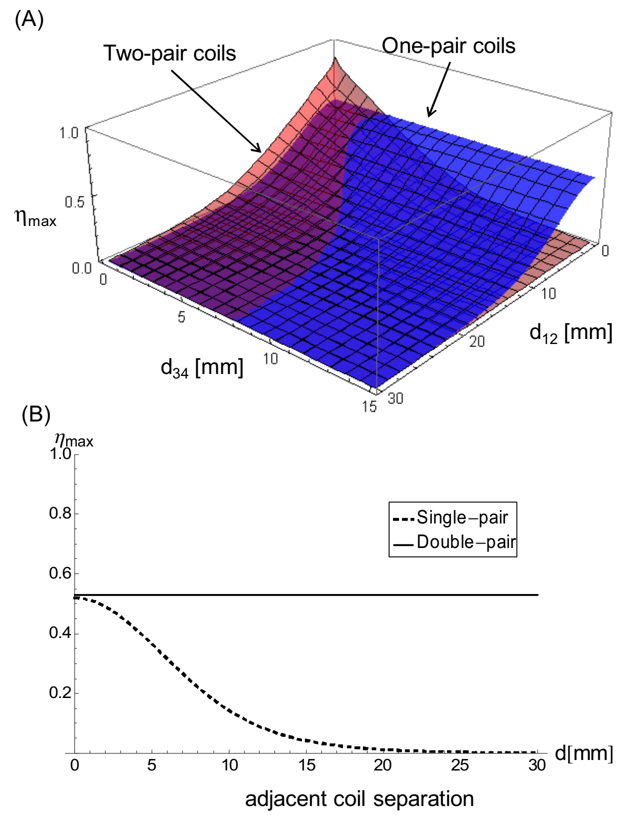

Fig. 3. (A) Simulated maximum efficiency values for varying coil separation for one-pair and two-pair coils. For the one-pair coil case, d_{34} does not exist and is plotted as an invariant, (B) comparison of maximum efficiency for one-pair coil at varying coil separation and two-pair coil when d_{12} = 5 mm and d_{34} = 0.5 mm.

For a quick analysis of power transfer efficiency, single turn coils are considered and mutual inductances are calculated analytically using Neumann's equation [6]. In order to determine maximum achievable efficiency, the following quantity is determined.

$$\psi_{12} = \frac{M_{12}^2 \omega^2}{R_1 \, R_2}, \tag{1}$$

where ω and R are the radial operating frequency and effective series resistance (ESR), respectively. The quantity ψ is a figure of merit for an inductive coil pair [7]. ESR is calculated by considering the dc and ac resistance of the coil. Maximum efficiency condition is reached when the resonance frequency of the primary and secondary coils is matched and an optimum load is connected to the secondary coil such that maximum power is transferred from the primary to the secondary side [8]. Under this condition, the maximum achievable frequency of the one-pair and two-pair coils system are given by

$$\eta_{one} = \left(\sqrt{1 + \frac{1}{\Psi_{12}}} - \sqrt{\frac{1}{\Psi_{12}}} \right)^2 \text{ and} \tag{2}$$

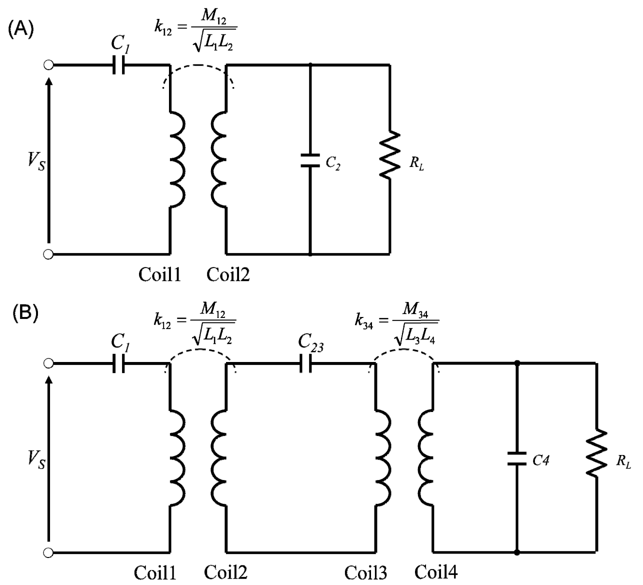

Fig. 4 Circuit schematic for (A) one-pair coils and (B) two-pair coils.

TABLE I
COMPARISON OF POWER TRANSFER EFFICIENCY

Configuration	Ave. load power [mW]	Efficiency[%]
One-pair coil	50.8	11.5
Two-pair coil	50.2	8.8

$$\eta_{two} = \left(\sqrt{1+\frac{1}{\Psi_{12}}} - \sqrt{\frac{1}{\Psi_{12}}}\right)^2 \cdot \left(\sqrt{1+\frac{1}{\Psi_{34}}} - \sqrt{\frac{1}{\Psi_{34}}}\right)^2, (3)$$

respectively. Evaluating (2) and (3) with the following conditions; $\omega = 2\pi$ Mrad/s, 0.01 mm diameter copper wires for the coils, $J_1 = J_2 = 10$ mm, and $J_2 = J_3 = J_4 = 5$ mm, for the one-pair and two-pair coils configuration, respectively, we obtain a plot as shown in Fig. 3. The plot in Fig. 3 (A) shows the maximum efficiency when coil separation is increased from 0 mm to 30 mm for d_{12} and 15 mm for d_{34}. The plot in Fig 3 (B) shows the maximum efficiency when $d_{12} = 5$ mm and $d_{34} = 0.5$ mm for the two-pair coils. This is close to the expected operating condition when implemented on a retinal prosthesis. From the plots it can be observed that efficiency falls as the separation is increased, as expected for both cases. However, the maximum efficiency achieved by the two-pair coils system at a fixed separation such as shown in Fig. 3 (B) can be considerably higher than the one-pair coils when it is operating with separation of higher than 5 mm. From this analysis, we deduce that the two pair coils system can potentially achieve higher power transfer efficiency compared to a one-pair coils design. This is in agreement to a study which uses a slightly different configuration for a two-pair coils system [9].

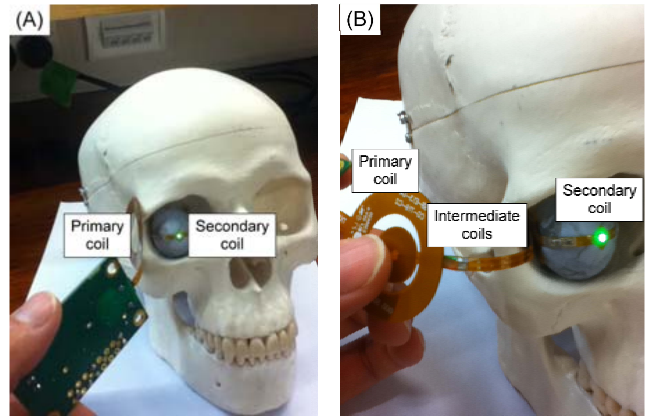

Fig. 5. Setup demonstrating wireless power transfer using, (A) one-pair and (B) two-pair coils system.

III. METHOD AND RESULT

A. Spice Simulation

In order to test out the two-pair coils system, we performed circuit simulation in SPICE (Fig. 4). The secondary coil is connected to a realistic but not optimum load $R_L = 220\,\Omega$. The coupling factors were calculated from the mutual inductance derived from the previous section and using inductance values of 16.7 µH and 2 µH for Coil1 and Coil2 for one-pair coils, while values of 16.7 µH is used for Coil1 and Coil2 and 2 µH is used for Coil3 and Coil4 for the two-pair coils system. The circuit was designed to resonate at 6.78 MHz and suitable matching capacitors are inserted in the circuit as shown in figure. The simulation result is shown in Table 1. Average load power is the amount of power consumed by the resistive load R_L at steady state, while efficiency is the ratio of load power to input power. This efficiency value is less than the maximum achievable values due to the fact that the load is not optimized. From the result, it can be seen that both one-pair and two-pair coils are capable of delivering 50 mW of power at similar efficiency levels. The source voltage V_S at the primary side for the two-pair coils needs to be higher compared to the one-pair coils case.

B. Physical Implementation

For realization, coils fabricated using flexible printed circuit technology are used [10]. They consist of 35 µm copper tracks sandwiched in between polyimide substrates which make a total thickness of about 0.2 mm. The primary coil consists of a 19 turns spiral with outer and inner diameter measuring 36.6 mm and 23.2 mm, respectively. The secondary coil is a 12 turn spiral with outer and inner diameter of 15 mm and 7.7 mm, respectively. The intermediate coils adjacent to the primary and secondary coils have the same dimensions. The spiral coil thinness and flexibility makes it very suitable for insertion into the eye. Figure 5 shows placement of the coils on a human

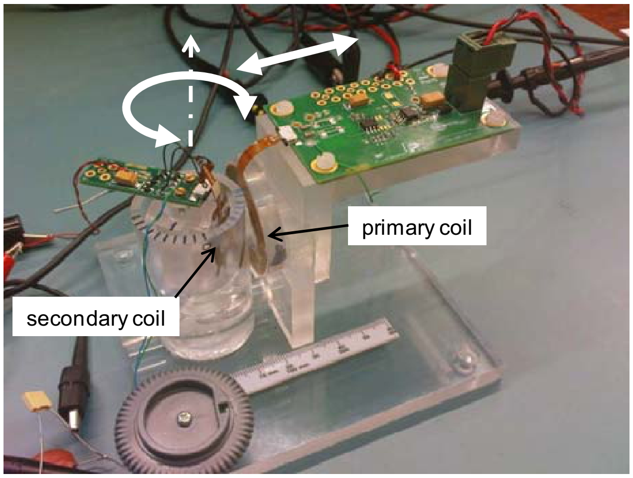

Fig. 6. Setup for characterizing wireless power transfer for the one-pair coil system.

head model. The larger transmit coil is connected to a driver circuit which is powered by a battery. The driver circuit generates a 6.3 MHz ac voltage which is used to drive the transmit coil. In order to operate the circuit at its optimal power transfer condition, a capacitor is connected in series to the transmit coil so that the circuit will resonate at close to 6.3 MHz. For the two-pair coils system, the intermediate coil adjacent to the transmit coil is placed directly under the transmit coil. It is connected to the coil at the other end through a matching capacitor so that the intermediate coils will also resonate at close to 6.3 MHz. For visualization, the secondary coil is placed on the eye instead of under the sclera. A frequency matching capacitor is connected in parallel to the receive coil. Finally, a 3.3V green LED (Agilent HSMM-C190-ND) is connected to the receive circuit to indicate that power is transmitted, thus successfully demonstrating wireless power transfer. It is worthwhile to note that the matching capacitors used need not be exact as the quality factor Q of the primary and secondary coils are not very high, typically about 50. However, techniques exist to optimize the topology of the tracks to increase Q [11].

C. Experiment

In order to characterize the power transfer coils, a jig was built which allowed for relative translational and rotational displacement between the coils (Fig. 6). A vector network analyzer (Agilent E5071C-440) was used to measure the S-parameters of the coils. Using the network analyzer we are able to determine single coil impedances as well as the coupling factor and maximum achievable efficiency for a pair of coils. In the first experiment, linear displacement between adjacent coil pair is varied and the maximum efficiency irrespective of load is measured. This was performed for both the one-pair and two-pair coils case. The measured result is shown in Fig. 7 (A). This result closely resembles the plot in Fig. 3 (A). In another

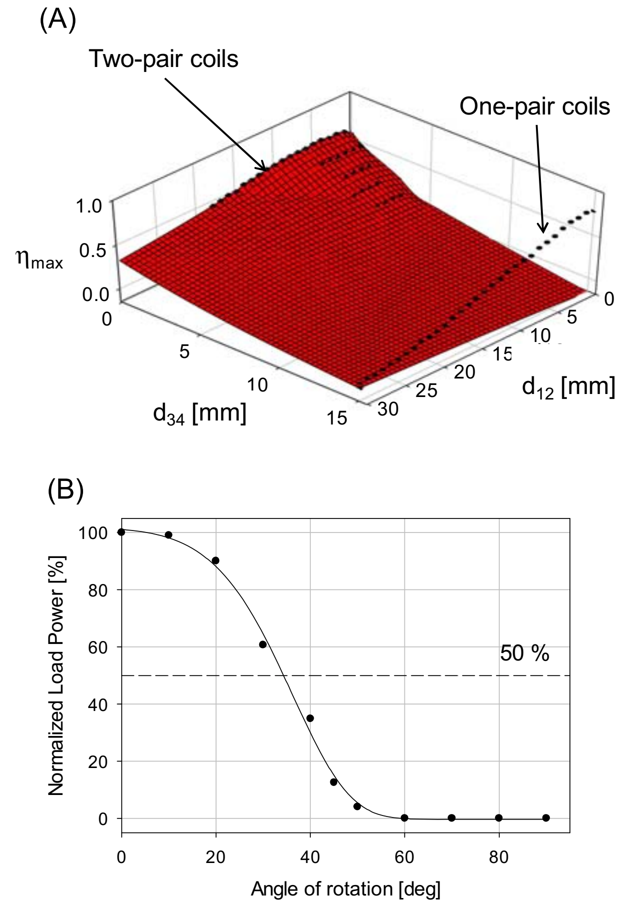

Fig. 7. (A) Plot of measured efficiency due to translational displacement between coils for one-pair and two-pair coils. (B) Plot showing rotational displacement between coils for one-pair coil.

experiment, a 220 Ω resistive load is connected to the rectified output of the secondary coil of the one-pair coils. The secondary coil was rotated about a vertical axis 20 mm away from the primary coil. The measured load power is normalized to the maximum power value at 0 deg rotation. The measured result is shown in Fig. 7 (B). The result shows that rotation causes a reduction in received power by more half when an axial misalignment of 35^0 or more is introduced.

We have applied a smaller modified version of the two-pair coils to an animal experiment. In the experiment, the secondary coil is inserted into the suprachoroidal space of the eye near the pars plane region. The primary coil is located on the skin around the head. One end of the intermediate coils is then placed under the skin adjacent to the primary coil with the other end placed on the sclera right above the secondary coil. The surgery required to place the coils in position is relatively easy compared to a full vitrectomy which would otherwise be required to implement a one-pair coils solution. We demonstrated that the two-pair coils are capable of transferring power wirelessly through skin and sclera of the eye.

IV. CONCLUSION

In this paper we have investigated the use of a one-pair and two-pair inductive coils for demonstrating wireless power transfer. Using the latter approach, we can overcome the problems associated with a one-pair coils system, where coupling variations and difficulty in surgery impede its adoption for use in a retinal prosthesis. There are no restrictions in using the two-pair coils system on different types of retinal implant locations; epiretinal, subretinal or suprachoroidal. We have successfully demonstrated power transfer above the 3.3 V threshold and 50 mW required by the implanted device using a two-pair coils solution.

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