35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Columnar Transmitter based Wireless Power Delivery System for Implantable Device in Freely Moving Animals

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Abstract— **A wireless power delivery system is developed to deliver electrical power to the neuroprosthetic devices that are implanted into animals freely moving inside the cage. The wireless powering cage is designed for long-term animal experiments without cumbersome wires for power supply or the replacement of batteries. In the present study, we propose a novel wireless power transmission system using resonator-based inductive links to increase power efficiency and to minimize the efficiency variations. A columnar transmitter coil is proposed to provide lateral uniformity of power efficiency. Using this columnar transmitter coil, only 7.2% efficiency fluctuation occurs from the maximum transmission efficiency of 25.9%. A flexible polymer-based planar type receiver coil is fabricated and assembled with a neural stimulator and an electrode. Using the designed columnar transmitter coil, the implantable device successfully operates while it moves freely inside the cage.**

I. INTRODUCTION

There has been growing interest in the field of neural prosthetic devices such as cochlear implant, retinal implant and deep brain stimulation for helping patients with neural disorders. Prior to clinical application of such devices, chronic animal experiments are essential to verify their efficacy as well as safety for an extended period of time. For successful animal experiments with neural prostheses, power delivery is one of the most challenging issues. While transcutaneous connection is easy to implement, this method can cause potential risk of infection and patient's discomfort. Although battery-integrated implantable device can eliminate the percutaneous wire, it is not suitable for long-term test due to limited life-time. Therefore, transcutaneous power transfer has been mainly used for wireless power delivery into implanted devices via inductive link consisting of a couple of coils, [1-6]. However, this method could guarantee high transmission efficiency only in a small transmission distance around only a few centimeters since the efficiency decreases rapidly as transmission distance increases. Therefore, when using conventional inductive link, external power transmitter should be attached on the animal, which may result in high probability of device failure due to continuous movement of animal.

A non-radiative wireless power transfer system based on electromagnetic resonance has been demonstrated that could achieve power efficiency higher than 40% over 2 m distance [7, 8]. We adopted this technology for wireless powering of biomedical devices implanted into freely moving animal inside a cage with greater efficiency and powering distance.

In this paper, we propose an animal–cage-based wireless power delivery system for long-term animal experiments using resonator-based inductive links. The transmitter coils are placed at the bottom of the animal cage and its structure was optimized to have columnar shape to achieve lateral uniformity of power efficiency. The planar receiver coil is integrated with a current stimulator and neural electrode.

II. SYSTEM DESCRIPTION

A. Overview

In this paper, we propose a novel power delivery system for animal experiments using implantable devices as shown in Figure 1. A small animal (e.g. rat or mouse) with an implanted device can move freely inside the cage (15cm×20cm×15cm, width×depth×height), while power is wirelessly transferred from transmitter coil attached at the bottom of the cage. The operating distance could be extended by adopting resonator based inductive links, and uniform power delivery over the surface plane could be achieved by designing the external coil in columnar structure.

The implantable device consists of a planar receiver coil, a neural stimulator, and an electrode. These are assembled and encapsulated by biocompatible silicone elastomer (MED-4215; Nusil Technology, Carpinteria, CA) [9]. The external transmitter consists of a columnar transmitter coil, and a class-E power amplifier which generates power with a frequency of 2.4576MHz. Capturing the power delivered from an external transmitter, the neural stimulator generates biphasic current pulses.

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*This work was supported in part by Korean Government R&D Projects, Ministry of Education, Science and Technology (20110001662, 20100020847), Ministry of Health and Welfare (A08459), ISRC of Seoul National University (SNU), and Ministry of Knowledge and Economy (10033657).

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978-1-4577-0216-7/13/$26.00 ©2013 IEEE

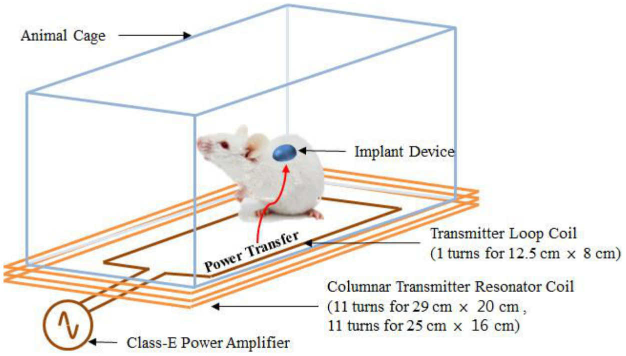

Figure 1. Schematic diagram illustrating an animal cage based wireless power transmission system. Resonator based inductive links are used to increase the power transmission distance. A columnar transmitter coil is proposed to achieve uniform power delivery over xy-plane. Using the proposed power deliver system, we could deliver power to the device implanted in freely behaving animal

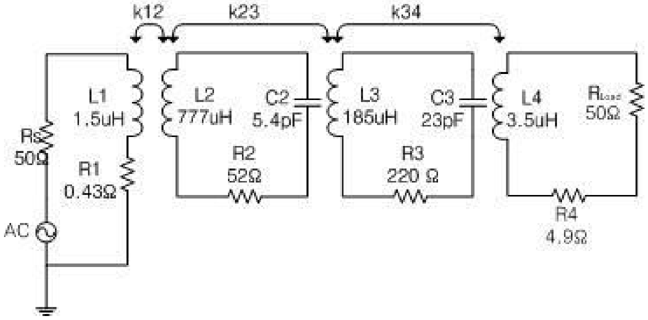

Figure 2. A schematic diagram showing resonator based inductive links. A transmitter loop coil (L1) drives a transmitter resonator coil (L2). The transmitter resonator coil (L2) and the receiver resonator coil (L3) are electromagnetically coupled to deliver power in long transmission distance. Finally, the receiver loop coil (L4) delivers power to the load

B. RF Coils

Resonator based inductive links are used to increase the power transmission distance as shown in Fig. 2. Unlikely the conventional inductive link, each transmitter and receiver is composed of two coils: high Q-factor resonator coil (L2, L3) and a loop coil (L1, L4) [7]. Using discrete capacitors, the transmitter resonator coil (L2) and the receiver resonator coil (L3) are tuned to maximize their electromagnetic coupling at the same resonant frequency of 2.4576MHz. The transmitter loop coil (L1) drives the transmitter resonator coil (L2), while the receiver loop coil (L4) receives the electromagnetic waves generated from the receiver resonator coil (L3) and sends the power to the load.

The columnar transmitter resonator coil (Fig. 3a) is designed to achieve uniforme power delivery while the receiver in the animal moves throughout the xy surface plane. We also designed the planar transmitter coil for comparison (Fig. 3b). The sizes and number of turns of these transmitters are identical: 29 cm x 20 cm for outermost dimension and 2 layers (11 turns per layer). The only difference between the columnar transmitter and the planar transmitter is the winding strategy which results in the different innermost dimension. The innermost dimension of the planar transmitter coil is designed as 15 cm x 5 cm. A litz-wire consisting of 100 strands of 48 AWG wire (HM Wire International, INC) is used to reduce the skin effect at the high operating frequency.

The planar receiver coil is fabricated on biocompatible liquid crystal polymer with copper clad by the dimension of 19 mm diameter and 250 um thickness as shown in Figure 4(b). To achieve high inductance of receiver resonator coil within the restricted area, we developed 4-layer stacking structure (19.5 turns per layer).

C. External Device

A class-E power amplifier is used to drive the transmitter loop coil, since this power amplifier is known to be efficient (ideally zero power loss) due to its zero-voltage switching [10, 11].

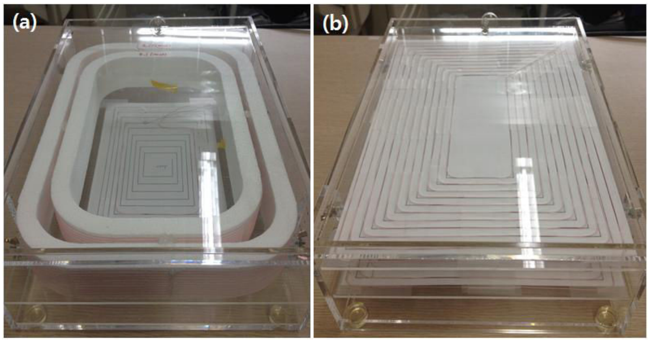

Figure 3. Photographs of two types of transmitter resonator coils. We designed and compared link efficiencies using (a) the columnar transmitter resonator coil, and (b) the planar transmitter resonator coil

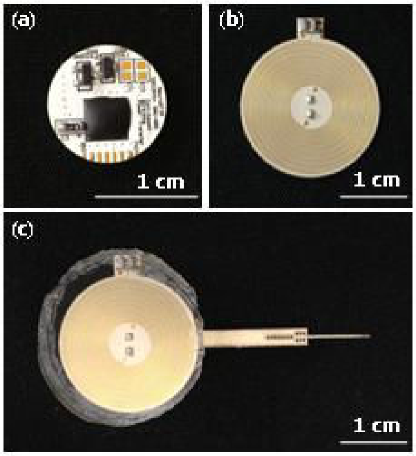

Figure 4. Photographs of an internal implant. (a) A neural stimulator, (b) a planar receiver coil, and (c) an integrated internal implant

D. Implant System

An implantable stimulator generating biphasic current pulses is designed. The neural stimulator is implemented on a ceramic PCB as shown in Fig. 4(a) integrating a rectifier and a regulator circuitreis to generate 3.0V stable DC voltage from the received signal. This 3.0V voltage is then fed into the stimulator IC [9].

Finally, the receiver coil, stimulator circuits, and electrodes are integrated and encapsulated using silicone elastomer as shown in Figure 4(c).

III. EXPERIMENTS AND RESULTS

Power transmission efficiency using proposed resonator-based inductive links were measured using a vector network analyzer (VNA, MS4630B, Anritsu, Japan). Efficiencies using the columnar transmitter resonator coil are compared to the planar transmitter resonator coil. As an indicator of stable power delivery, a light emitting diode (LED) was connected to the receiver loop coil. Finally, functionality of the neural stimulator while moving inside the cage was verified by measuring the biphasic current pulses generated from the neural stimulator using a oscilloscope.

A. Power Transmission Link Efficiency

To measure the link efficiency, the port 2 is connected to the transmitter loop coil while the port 1 is connected to the receiver loop coil. The S_{21} value is measured and the power transmission link efficiency can be calculated using (1) [12].

$$\text{Efficiency}\ (\%) = |S_{21}|^2 \times 100 \qquad (1)$$

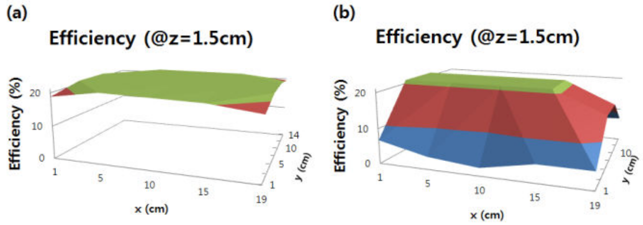

Figure 5. Graphs of power transmission links efficiencies using two types of transmitter resonator coils. Using the columnar transmitter resonator coil (a), only 7.2% efficiency fluctuation occurs from the maximum efficiency of 25.9% while, (b) 29.8% efficiency fluctuation occurs from the maximum efficiency of 31.9% when using the planar transmitter resonator coil

Efficiency and its lateral variation was compared for the columnar transmitter resonator coil and the planar transmitter resonator coil while moving the receiver within the cage at 1cm above the bottom plane as shown in Fig. 5. Using the columnar transmitter resonator coil, the maximum transmission efficiency was obtained as 25.9% while 31.9% was measured using the planar transmitter coil. However, low efficiency variation, 28 % (7.2 % efficiency fluctuation), is obtained using columnar transmitter resonator coil, while 93 % (31.9 % efficiency fluctuation) is achieved using the planar transmitter resonator. The planar transmitter shows greater efficiency in the center than that of the columnar transmitter, but efficiency drops rapidly as receiver moves toward the edge. Therefore, we could guarantee lateral uniformity of power delivery by using the columnar transmitter resonator coil.

B. Power Transmission Test

An LED connected to the receiver loop coil is used to qualitatively show the power is being stably delivered throughout the cage area via resonator based inductive links as shown in Figure6 (a). Multiple receivers can be powered simultaneously as shown in Figure 6 (b). A load resistor is connected to the receiver coil for measuring the amount of power delivered to the load. The power delivered to the load is calculated to be 43 mW.

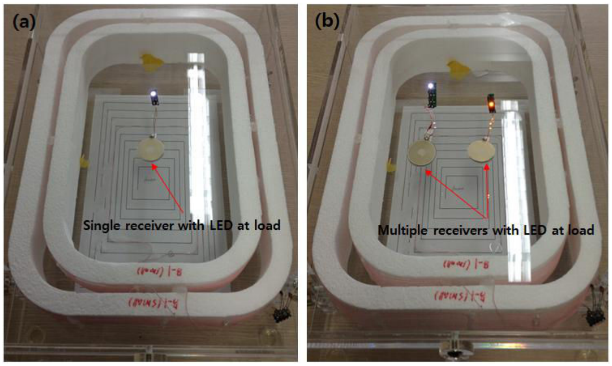

Figure 6. Photographs showing the transmitter and (a) single or (b) multiple of receivers with LED connected to the receiver. Multiple of LEDs are lighted simultaneously utilizing the power transmitted from transmitter

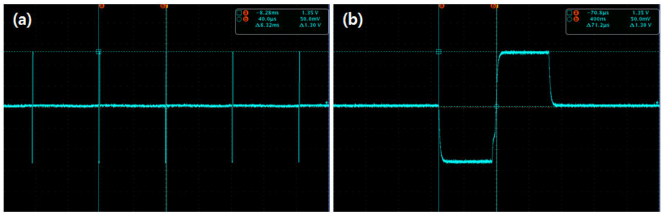

Figure 7. Photographs of measured biphasic pulses voltage signals. These pulses are generated from neural stimulator chip utilizing the power transmitted from transmitter. Amplitude, frequency, and duration are measured as 2.6 V (at 75 kΩ load), 120 Hz, and 71 μs, respectively

Biphasic current pulses are generated from the stimulator circuit powered by the transmitter coils. Amplitude, frequency, and duration of these pulses were measured as 2.6 V (with 75 kΩ load), 120 Hz, and 71 μs, respectively as shown in Figure 7. These pulses can be stably generated within the cage regardless of location of the receiver coil.

IV. CONCLUSION

An animal cage with wireless power delivery system for long-term experiments using freely moving animal implanted with devices was developed. Power efficiency could be improved by using resonant-based inductive link and the lateral efficiency variation was minimized by creating columnar transmitter coil. This system could be implemented into the animal experiments of neural prosthetic devices as well as other medical implantable devices.

REFERENCES

[1] Catrysse, M., Hermans, B., and Puers, R.: 'An inductive power system with integrated bi-directional data-transmission', Sensors and Actuators A: Physical, 2004, 115, (2-3), pp. 221-229

[2] Lenaerts, B., and Puers, R.: 'Inductive powering of a freely moving system', Sensors and Actuators A: Physical, 2005, 123-124, (0), pp. 522-530

[3] Carta, R., Thoné, J., and Puers, R.: 'A wireless power supply system for robotic capsular endoscopes', Sensors and Actuators A: Physical, 2010, 162, (2), pp. 177-183

[4] Zierhofer, C.M., and Hochmair, E.S.: 'High-efficiency coupling-insensitive transcutaneous power and data transmission via an

inductive link', Biomedical Engineering, IEEE Transactions on, 1990, 37, (7), pp. 716-722

[5] Chaimanonart, N., Zimmerman, M.D., and Young, D.J.: 'Adaptive RF power control for wireless implantable bio-sensing network to monitor untethered laboratory animal real-time biological signals', in Editor (Ed.)^(Eds.): 'Book Adaptive RF power control for wireless implantable bio-sensing network to monitor untethered laboratory animal real-time biological signals' (2008, edn.), pp. 1241-1244

[6] Young, D.J.: 'Wireless powering and data telemetry for biomedical implants', in Editor (Ed.)^(Eds.): 'Book Wireless powering and data telemetry for biomedical implants' (2009, edn.), pp. 3221-3224

[7] Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J.D., Fisher, P., and Soljacic, M.: 'Wireless power transfer via strongly coupled magnetic resonances'. Proc. Science, Jul 6 2007 pp. Pages

[8] Kurs, A.: 'Power Transfer Through Strongly Coupled Resonances', MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2007

[9] Lee, T.H., Pan, H., Kim, I.S., Kim, J.K., Cho, T.H., Oh, J.H., Yoon, Y.B., Lee, J.H., Hwang, S.J., and Kim, S.J.: 'Functional regeneration of a severed peripheral nerve with a 7-mm gap in rats through the use of an implantable electrical stimulator and a conduit electrode with collagen coating', Neuromodulation, 2010, 13, (4), pp. 299-304

[10] Kazimierczuk, M.K.: 'RF Power Amplifier' (Wiley, 2008, 1st edn. 2008)

[11] Kendir, G.A., Wentai, L., Guoxing, W., Sivaprakasam, M., Bashirullah, R., Humayun, M.S., and Weiland, J.D.: 'An optimal design methodology for inductive power link with class-E amplifier', Circuits and Systems I: Regular Papers, IEEE Transactions on, 2005, 52, (5), pp. 857-866

[12] Imura, T., and Hori, Y.: 'Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula', IEEE Transactions on Industrial Electronics, 2011, 58, (10), pp. 4746-4752