A Novel 3-D Printed Headstage and Homecage based WPT System for Long-term Behavior Study of Freely Moving Animals

Dipon K. Biswas, Jose H. A. Martinez, Jacob Daniels, Abhijeet Bendapudi, and Ifana Mahbub
Department of Electrical Engineering, University of North Texas, Denton , TX 76207, USA

***Abstract*—Wirelessly powered neural stimulation and recording system is crucially important for the long-term study of the animal behaviors for the treatment of chronic neuropathic diseases. Headstage based neural implant is one of the popular methods to stimulate the neurons. In this work, a homecage based wireless power transfer (WPT) system is developed to supply power to a 3-D printed headstage which consists of a receiver (RX) coil, a rectifier and a light-emitting diode (LED) for optogenetic stimulation. A multilayer transmitter (TX) coil is designed to provide power over the 28.5 cm $\times$ 18 cm homecage area. The proposed system is able to achieve a maximum of 41.7% efficiency at 5 cm distance through air media using less number of headstage resonators compared to the other state-of-the art works.**

***Index Terms*—Wireless power transfer (WPT), homecage, headstage, 3-D print, power transfer efficiency**

I. Introduction

Long-term monitoring of neural signal has become very popular for the treatment of chronic neural diseases such as Parkinson's and chronic neuropathic pain. Deep brain stimulation and neuromodulation is an essential part of these treatments [1]. Implanted wireless neural interface and microsystems can be used to continuously monitor neural activities of freely moving animals [2]. Conventional neural interfaces use transcutaneous wires and external batteries to supply power to the active circuitry. However, transcutaneous wires interrupt the study of the neural behavior of the freely moving animals [3]. Moreover, the batteries need to be replaced after a certain period of time. Chemical leakage from the batteries and the tethered wire connection also poses a risk of infections. To avoid the use of wires and batteries, WPT system for neural interfaces utilizing inductive coupling technique is presented in recent work [4].

Headstage and homecage based WPT system has become very popular in brain neuromodulation applications such as Optogenetic and electrical stimulation. To ensure constant field distribution all through the homecage, resonator coils are wrapped around the cage as shown in Fig. 1 [5], [6]. The whole system typically consists of a transmitter (TX), homecage resonators and a headstage module. The headstage can be mounted on the head of the freely moving animal i.e., mouse or rat. The TX is designed to generate electric fields all across the homecage to ensure the required power to be delivered to the headstage for the neural stimulation. In [7], a headstage module with five resonator coils is presented which make the headstage bulky. However, the headstage needs to be lighter to successfully analyze the behavior of the freely moving animal.

In this paper, a 3-D printed headstage and homecage based WPT system is designed to power the headstage module. The novelty of this work are as follows: (1) the headstage module is designed with reduced number of resonators which make the headstage light-wieght, (2) a multilayer TX coil is designed to supply power to the whole homecage and headstage. The rest of the paper is organized as follows: the design architecture of the homecage based WPT system is presented in section II, followed by the experimental results in section III. A concluding remark is presented in section IV.

II. Architecture Of The Homecage Based WPT System

As shown in Fig. 1, the proposed home-cage based WPT system includes three subsystems: a planar TX coil, homecage with resonators, and the headstage. Fig. 2 shows the electrical modeling of the proposed WPT system. The TX coil denoted by L_1 is connected to the signal generator and C_{R_TX} represents the resonating capacitor of the TX coil. The homecage system consists of six copper tape based coils denoted as L_2-L_7. To resonate the inductance of the coils wrapped around the homecage, the resonating capacitors, C_{R_HC} are added. The next stage is the headstage module which is divided into two sections: one is the resonator and the other is the RX module. The resonators can be modeled as an inductor-capacitor based system where L_8, and L_9 denotes the two inductor coils and C_{R_R} represents the resonating capacitance. The RX module has three components: an RX coil represented as L_{10} along

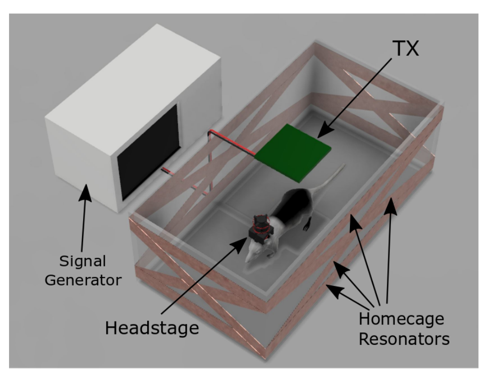

Fig. 1: System overview of the proposed homecage based WPT system

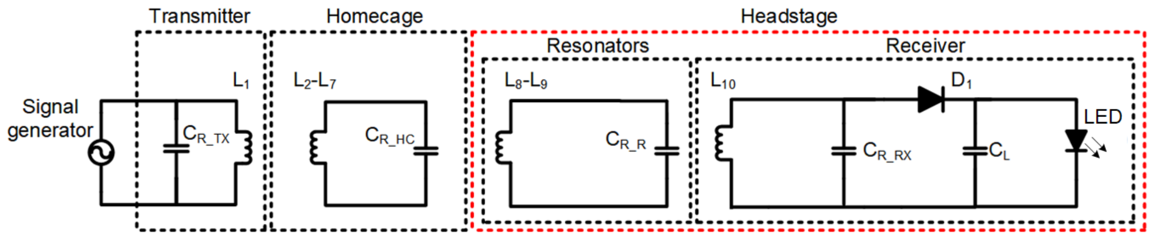

Fig. 2: Equivalent electrical modeling of the proposed wireless power transfer system

with the resonating capacitor, C_{R_RX}, rectifier, D_1 and a μLED for optogenetic neuromodulation. A load capacitor, C_L is added after the rectifier to make the signal smoother. To regulate the voltage to a constant DC voltage the voltage regulator could be added, or a closed-loop power regulation system can be designed.

A. TX Architecture

The TX subsystem consists of a multilayer planar TX coil designed on a printed circuit board (PCB) with a total dimension of 23.4 cm $\times$ 19.7 cm as shown in Fig. 3(a). The top layer has nine identical spiral coils, each of a 36 cm^2 dimension connected in series. Similarly, the second layer has four coils in series and connected in series to the top layer using a via connection. A resonating capacitor of 22 pF is used to resonate the TX coil at 13.56 MHz. However, the added capacitance due to soldering and other parasitic capacitances reduce the frequency to a lower value of 13.26 MHz. To boost the power, an RF power amplifier (PA) (MACOM MAAM-011162) with a flat gain of 18 dB is also intended to be added in case the distance of operation is increased or the LED requires higher intensity during the *in-vivo* measurement.

B. Homecage Resonators

For observing the behavior and the movement of mice, a conventional homecage is used in this work with a dimension of 28.5 cm $\times$ 18 cm $\times$ 13 cm as shown in Fig. 3(b). Six single-turn coils, L_2-L_7 are used to wrap around the cage to create the resonators. The resonators are used to increase the total magnetic field and strengthen the coupling between the TX and RX coils. The resonators are fabricated using copper tape with a width of 25 mm, each isolated by a layer of Kapton tape to avoid the shorting between the overlapping coils. There are three groups of identical resonators according to the length, and inductance. The value of the resonators' lengths and inductances are listed in Table. I. All of the resonators are designed to resonate at 13.26 MHz, similar to the TX coil.

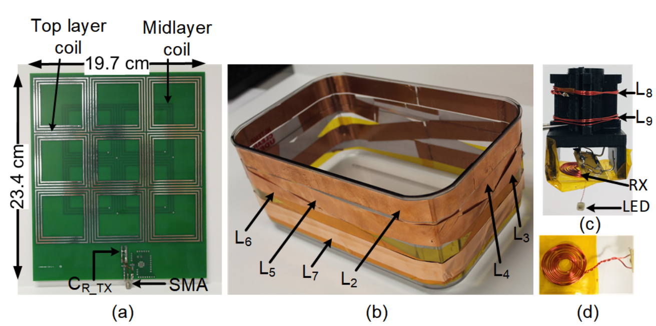

Fig. 3: Fabricated (a) TX coil, (b) homecage, (c) 3-D printed headstage, and (d) RX coil

TABLE I
Coil dimensions and parameters.

Sub-system	Coil	Length, cm	Inductance, μH
TX array	L_1		4.37
Homecage	L_2, L_7	96	0.89
	L_3, L_6	93	0.86
	L_4, L_5	95	0.88
Headstage	L_8, L_9	23.5	0.42
	RX		1

C. Headstage Resonators and RX Architecture

The headstage is 3-D printed using the Creality Ender 3 and 1.75 mm Polylactic acid (PLA) filament. The headstage includes two resonator coils L_8, and L_9, RX module and a LED connected using 38 AWG wire. The idea is to implant about 10 mm of the wire and the LED inside the head of the animal making a small incision. The headstage is strategically designed to allow L_8, and L_9 to fit at their respective placements for maximum power transfer efficiency. The resonators are made of Remington 26 AWG solenoid wires with 3 turns. The total dimension of the headstage is to be 2.6 mm $\times$ 2.6 cm $\times$ 3.5 cm and the weight of the headstage is measured to be 10 g. The distance between the two resonators is set to be 1 cm and the RX coil is placed 2 cm below the resonator, L_9 as shown in Fig. 3(c). The RX coil is a planar circular spiral coil with 10 turns as shown in Fig. 3(d). The diameter of the coil is 1.8 cm which can be easily attached underneath the headstage. A resonating capacitor of 133 pF is used to resonate the RX coil at 13.26 MHz. A schottky diode (CUSO8F30 by Toshiba) is used as a half-wave rectifier after the RX coil to provide the DC voltage to the LED (OSRAM opto-semiconductors LB-QH9G, forward bias voltage-2.6 V, current-5 mA, power-12 dBm). The μLED is soldered at the tip of a 10 mm long wire so that the system can be used for the stimulation at the hippocampus part of the brain.

III. Experimental Results

The fabricated TX coil, homecage and headstage resonators, and RX coil of the proposed system are validated through measurement. The manufactured coils are individually characterized using the Keysight E5061B Vector Network Analyzer (VNA). All the coils are resonated at 13.26 MHz frequency

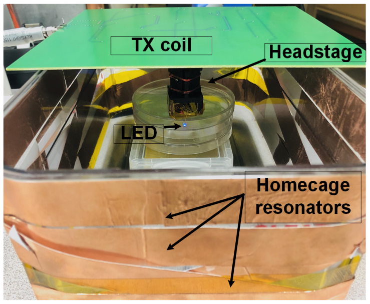

Fig. 4: Testbench setup showing the LED light for the homecage and headstage based WPT system

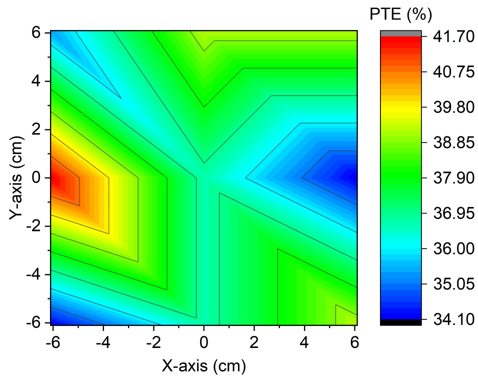

Fig. 5: Measured PTE for homecage WPT System

using Johanson Dielectrics SMD chip capacitors of the respective values required for each coil. The TX coil is connected with a Keysight N5171B EXG Analog Signal Generator which can provide a maximum of 19 dBm (79 mW) power. The fabricated TX coil is placed on top of the homecage as shown in the testbench in Fig. 4. The distance between the TX coil and RX coil is measured to be 5 cm and at this distance, the proposed system is able to supply 13 mW power which is the minimum amount of power required to light up the LED. To test the validity of transferring power all over the cage, nine different coordinate points have been selected inside the cage which are 5 cm far from the TX coil.

The VNA is used for measuring the insertion loss, S_{21} for L_{TX} and L_{RX} at the selected coordinates at 5 cm distance between the TX and the RX coils which is used to measure the PTE as shown in Fig. 5. It can be seen that the efficiency varies with positions. With the variation of the efficiency, the intensity of the LED also varies. It is seen from the measurement that the LED experiences the highest intensity at 41.7% efficiency when the transmitted power is 19 dBm and the received power is 15 dBm. The LED is barely turned on when the PTE is 34.1% and received power is 14.3 dBm at different coordinates with the same transmitted power. It is evident that if the PTE is greater than 34.1%, the power delivered to the load (PDL) is sufficient enough to illuminate the LED. Table 2 shows a comparison of this work with previous works. It can be seen that this work is able to achieve a higher PTE than other prior works while maintaining similar coil configurations and also using a smaller RX diameter.

TABLE II
Comparison with Other Works

Reference	[5]	[6]	[8]	This work
Carrier frequency (MHz)	13.56	13.56	2.45	13.26
Coil configuration	4 coil	3/4 coil	4 coil	4 coil
Powering distance (cm)	0-17	7	1.5	5
RX diameter (cm)	2.2	2.5	2	1.8
PTE (%)	18	21.9	25.9	34.1 (Min) 41.7 (Max)

IV. Conclusion

A homecage and 3-D printed headstage based WPT system is developed in this work and experimentally characterized to deliver sufficient power to illuminate an LED in the headstage. While using a headstage module with reduced number of resonators, the PTE for the entire system is designed to be in the range of 34- 42% range in order to illuminate the LED for optogenetic stimulation. A multilayer TX coil to power the headstage module also assists in delivering power to the entire homecage while resonators around the cage assist in distributing the power evenly. Future modifications include optimization of each of the resonator coils in regards to the number of turns and separation distance on the headstage for optimal efficiency as well as the integration of voltage regulators on the headstage to provide constant power to the load. Additional integration of a PA with the TX coil to assure the LED will remain on at all coordinates and an RFID tag to eliminate the need for the signal generator will also be implemented in the future.

References

[1] Y.-P. Lin, C.-Y. Yeh, P.-Y. Huang, Z.-Y. Wang, H.-H. Cheng, Y.-T. Li, C.-F. Chuang, P.-C. Huang, K.-T. Tang, H.-P. Ma *et al.*, "A battery-less, implantable neuro-electronic interface for studying the mechanisms of deep brain stimulation in rat models," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, no. 1, pp. 98–112, 2015.

[2] A. M. Aravanis, L.-P. Wang, F. Zhang, L. A. Meltzer, M. Z. Mogri, M. B. Schneider, and K. Deisseroth, "An optical neural interface: in vivo control of rodent motor cortex with integrated fiberoptic and optogenetic technology," *Journal of Neural Engineering*, vol. 4, no. 3, p. S143, 2007.

[3] S. A. Mirbozorgi, H. Bahrami, M. Sawan, and B. Gosselin, "A smart cage with uniform wireless power distribution in 3d for enabling long-term experiments with freely moving animals," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, no. 2, pp. 424–434, 2015.

[4] M. Kiani, U.-M. Jow, and M. Ghovanloo, "Design and optimization of a 3-coil inductive link for efficient wireless power transmission," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 5, no. 6, pp. 579–591, 2011.

[5] S. A. Mirbozorgi, Y. Jia, D. Canales, and M. Ghovanloo, "A wirelessly-powered homecage with segmented copper foils and closed-loop power control," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, no. 5, pp. 979–989, 2016.

[6] B. Lee, M. Kiani, and M. Ghovanloo, "A smart wirelessly powered homecage for long-term high-throughput behavioral experiments," *IEEE Sensors Journal*, vol. 15, no. 9, pp. 4905–4916, 2015.

[7] Y. Jia, S. A. Mirbozorgi, Z. Wang, C.-C. Hsu, T. E. Madsen, D. Rainnie, and M. Ghovanloo, "Position and orientation insensitive wireless power transmission for enercage-homecage system," *IEEE Transactions on Biomedical Engineering*, vol. 64, no. 10, pp. 2439–2449, 2017.

[8] K. Eom, J. Jeong, T. H. Lee, J. Kim, J. Kim, S. E. Lee, and S. J. Kim, "A wireless power transmission system for implantable devices in freely moving rodents," *Medical & Biological Engineering & Computing*, vol. 52, no. 8, pp. 639–651, 2014.