Towards a Wireless Optical Stimulation System for Long Term In-Vivo Experiments

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Abstract—**This paper presents our recent progresses towards the development of a wirelessly powered head mountable optical stimulator for enabling long-term optogenetic experiments with small freely moving transgenic models. The proposed system includes a wireless power transmission chamber with uniform power distribution in 3D and a wireless head mountable optical stimulator prototype with power recovery. The wireless power link, which includes the inductive chamber and power recovery circuits, is robust against subject movements in all directions, and against angular misalignment. Such link provides uniform power distribution without the need for a closed-loop control system, and can localize the transmitted power towards the receiver, without using additional detection and control circuitry compared to other systems. Additionally, the chamber is equipped with a camera for capturing the animal motion and behavior after applying optical stimulation patterns. A low-power microcontroller unit is embedded with the stimulator prototype to generate arbitrary light stimulation patterns. Measurement results show that the inductive chamber can continuously deliver 70 mW to the stimulator prototype with a power efficiency of 59%.**

I. INTRODUCTION

Smart implantable devices are becoming highly sought in modern medicine. These devices have a wide range of applications such as health monitoring, disease treatment and biomimetic prosthesis. Direct neuronal stimulation using electrical or optical means is the basis of several new emerging treatments and neuroprostheses [1-7]. Studying elicited neuronal activity through direct neuronal stimulation in freely moving animals, with observable behavior, is critical for advancing our understanding of the brain [8, 9]. Miniature head mountable electronic devices have been developed to stimulate the brain and to record the neural response in small rodents [1], [5], [10-12]. However, such devices are most often tethered to a remote power and/or light source, which leads to several limitations caused by cables like sheer stress, prohibitive weight and increased risks of infection [13]. Wireless head mountable optical stimulators are therefore highly sought for this application [4], [5], [14-16]. However, using a small battery for driving an embedded optical stimulation source is not practical since LEDs or VECSELs require high power that is only available from a large and usually cumbersome battery.

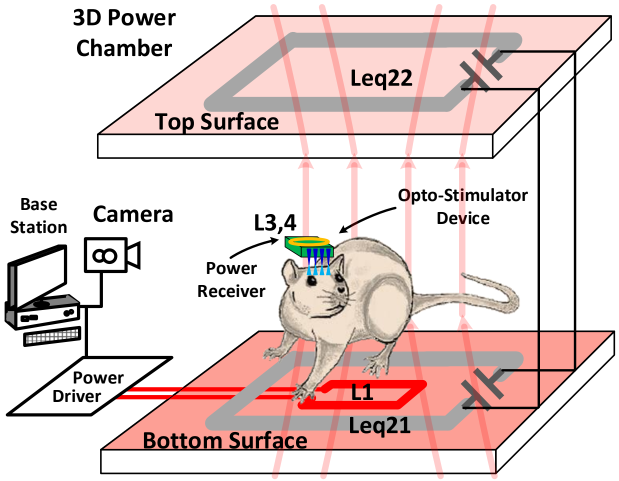

Fig. 1. Conceptual representation of the proposed wireless optical stimulator system including wireless power transmission and motion tracking.

High-efficiency wireless power transmission links based on inductively coupled coils are used as battery chargers or as short-range standalone wireless power sources [17-20]. Designing a wireless power transmission link for this application is very challenging since it must be highly efficient and robust to motion and angular misalignments of the power-receiver. The power transfer efficiency obtained with an inductive link strongly depends on the geometry of the coils, the separation distance between the transmitter (TX) and the receiver (RX), and their orientation (angular alignment). Wireless power transmission chambers have been designed to power up small electronic systems. The chamber can use a single big coil, the size of the chamber, or an array of smaller coils [17], [19-22]. Using a chamber the bottom of which is tiled with smaller TX coils has proven much more efficient than one with a single big coil that encompasses the whole area [19-22]. In fact, arrays of coils can provide homogeneous magnetic flux density within the entire chamber area. The uniformity of the magnetic field can also be further improved by using multiple overlapped power RX coils [20].

An important issue with inductive arrays is power localization. Power localization focuses the transmitted power at the location of the power RX coil, so no resource is wasted [19-21]. Different techniques have been used to avoid driving all coils of an array simultaneously [13], [20-22]. In [20], a magnetic sensor is used to detect the location

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This work was supported, in part, by the Natural Sciences and Engineering Research Council of Canada, the Fonds de recherche du Québec - Nature et technologies and by the Microsystems Strategic Alliance of Quebec. S. A. Mirbozorgi, R. Ameli and B. Gosselin are with the Dept. of Electrical and Computer Eng., Université Laval, Quebec, QC G1V 0A6, Canada (phone: +1(418) 656-2131; e-mail: sa.mirbozorgi@gmail.com.) M. Sawan is with Polystim Neurotechnologies Laboratory, Dept. of Electrical Eng., Polytechnique Montréal, Montréal.

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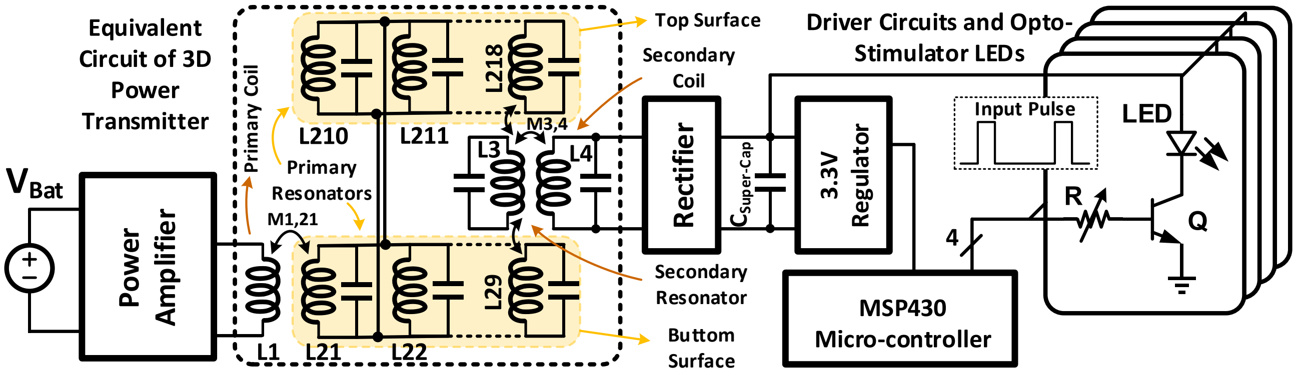


Fig. 2. Block diagram of the proposed wireless optical stimulator system including a power amplifier, a uniform 3D power transmission link and an optical stimulator prototype. Such prototype includes, power receiver coils, power recovery circuits, a microcontroller, four LEDs and associated driver circuits.

of a small magnet embedded in the RX and to activate the subset of coils that encompass the RX using dedicated control circuitry. On the other hand, a closed-loop power control mechanism must be utilized to compensate the power variations when the receiver is moved in the z direction. Such control systems are difficult to be implemented because they need a data link and associated circuitry to sense and transmit the amount of the delivered power in real time [19].

We have previously proposed a power RX surface based on a multi-coil link that includes several primary resonator coils, which provides natural power localization [22] without the need of complex detection and control circuitry. This work presents a wireless optical stimulator system enabling wireless power transmission using a multi-coil inductive link and motion tracking. The inductive chamber provides uniform power distribution in 3D using a novel parallel multi-coil array, previously presented in [22]. The whole system is experimentally tested and the results are presented in this paper. Section II gives an overview of the proposed system, and Section III presents the measurement results of the whole wireless optical stimulator system. Finally, conclusions are drawn in Section IV.

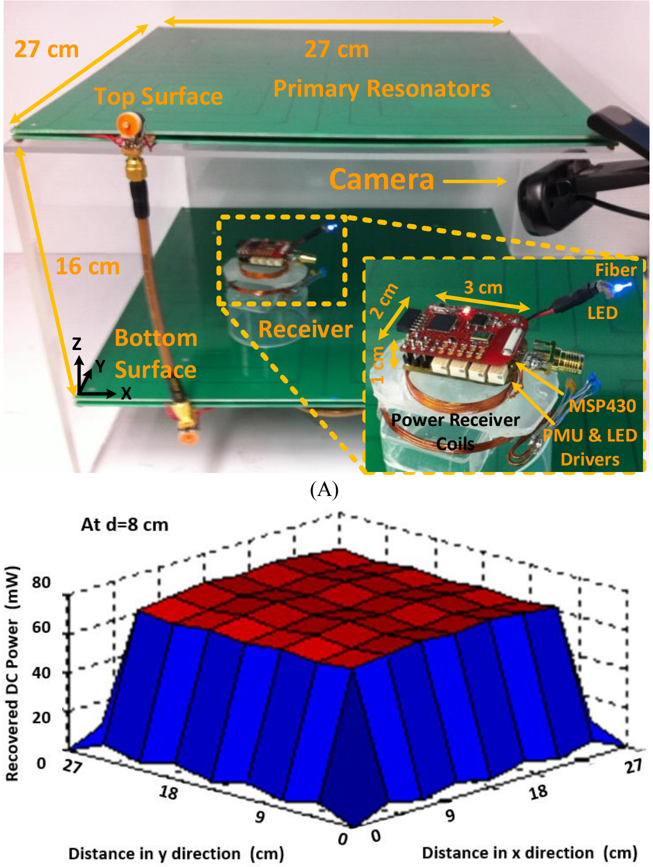
II. SYSTEM OVERVIEW

Fig. 2 shows the block diagram of the proposed wireless optical stimulator. The power link includes a Class-E power amplifier, a power chamber as power transmitter, and a power receiver. The power chamber includes an array of overlapping coils separated within two surfaces (top and bottom) for providing uniform power in 3D. The power receiver is embedded into the head mountable stimulator, and includes a secondary resonator coil and a secondary RX coil. The power TX chamber and the power RX form a four-coil inductive link [18]. The optical stimulator prototype also includes a power rectifier, a super-capacitor, a 3.3-V regulator, a low-power MSP430 microcontroller unit (MCU), four LEDs and four LED driver circuits.

The purpose of the wireless head mountable unit is to generate optical stimulation patterns. The power consumption of such head mountable device is dominated by the light source (an LED in that case) [9]. Resonance-based inductive links are high efficiency topologies that can provide the required power for driving LEDs in such an application [18]. The proposed optical stimulator is battery-less and is harvesting its power from an electromagnetic field provided by the power transmission chamber. The electromagnetic field inside the chamber is generated by an array of overlapping coils located at the bottom and on the top of chamber. Such overlapped arrays result in a uniform electromagnetic everywhere inside the chamber. Moreover, overlapped coils are all connected in parallel, which structure provides localized power transmission towards the RX [22]. Such a mechanism makes the design and the implementation of the power chamber simple and cost-efficient.

The top and bottom surfaces of the chamber include 18 overlapped primary resonators, which are all connected in parallel with wires. The inductive power link is based on a 4-coil structure the resonance frequency of which is tuned at 13.56 MHz. These overlapped primary resonators cover a large area over which a head mountable unit equipped with a power receiver can experience uniform power distribution. Moreover, the transmitted power is localized by recruiting the primary resonators that are located right under the power RX. Arrays of overlapped primary resonators provide uniform power distribution along x and y directions. Additionally, using to surfaces (top and bottom) allows uniform power distribution along the z direction as well. As the stimulator moves towards the top, the power received from the bottom coil arrays is decreased, whereas such a drop is compensated by more power from the coil arrays of the top surface.

The received power is rectified in the head mountable prototype by a diode-bridge and is regulated by 3.3-V regulator. A super-capacitor is utilized to decrease the ripple at the rectifier output voltage and to store the received power. The MSP430 MCU generates the required stimulating patterns. The LED driver circuitry includes potentiometers and BJT transistors to turn LEDs on and off, and to control the driving current in each LED. This system allows controlling 4 optical stimulation LEDs to provide programmable pulse width modulated optical stimulation patterns with pulse durations between 10 to 100 ms. A camera is used for motion tracking and to record the behavior of the animal model. The camera is located in the top of the chamber and captures the entire chamber interior. The recorded video data can be studied offline to investigate the effects of optical stimulation on animal behavior.



(A)

(B)

Fig. 3. A) Implemented optical stimulator prototype enabling uniform power distribution in 3D and B) measurement results of the recovered DC power (rectifier output, power delivered to the load) as a function of *x* and *y* axis at d=8 cm.

III. EXPERIMENTAL RESULTS

Fig. 3-A shows the prototype of the proposed wireless optical stimulator system. It includes the 3D power chamber, a camera for motion tracking and the head mountable optical stimulator prototype with an embedded MSP430 and four LEDs. The coil elements of the power transmitter arrays are implemented using squared spiral printed copper tracks into FR4. The size of chamber, which is made of transparent plexiglass, is 27×27×16 cm^3. The size of the head mountable stimulator prototype equals 1×2×3 cm^3. Two power surfaces (top and bottom) connected in parallel are employed to implement the 3D power chamber (Fig. 3-A). The 3D power chamber prototype includes 18 overlapped primary resonance coils connected in paralleled with wires. The separation distance between both top and bottom surfaces is 16 cm, and the effective volume with uniform power distribution of the 3D power chamber is 22.5×22.5×14 cm^3. The measured PDL inside the 3D power chamber equals 100 mW, while the rectified power is 70 mW. Fig. 3-B presents the recovered power (output of the rectifier circuit) versus the *x* and *y* axes, when the stimulator prototype is at a distance of 8 cm from the chamber top and bottom surfaces (d = 8 cm). The maximum variation of the recovered power inside the chamber is 5 mW. The efficiency of the power link and the rectifier circuit are 59% and 70%, respectively. The power consumption of the embedded MSP430 is 1 mW, and the four LED consume up to 69 mW continuously. A 1-Hz pulse with a 100-ms pulse-width was utilized for this test. A 220-mF super-capacitor, connected in parallel with the LEDs, allows driving the LEDs with high discharge currents to provide high optical power. The power link provides the stimulation circuitry with an uninterrupted DC current of 20 mA. Such power is accumulated in the super-capacitor between each pulse-width duration to drive the LEDs with high currents of more than 20 mA during stimulation periods.

TABLE I
SPECIFICATION OF THE WIRELESS OPTICAL STIMULATOR PROTOTYPE

Parameter	**Value**
Type of inductive link	4-coil
Power link efficiency	59%
DC power delivery	70 mW
Size of Chamber	27×27×16 cm^3
Diameter of receiver coil	4.2 cm
Size of head mountable prototype	1×2×3 cm^3
Number of opto-stimulation channel	4
MCU power consumption	1 mW

The proposed chamber does not need additional closed-loop power control mechanism to adjust the power against movement along the *z* axis. When the separation distance (d) between the bottom surface and the RX increases, less power is delivered by the bottom surface, whereas the top surface compensates such power drop by providing more power. As a result, PDL (as well as PTE) of the 3D power chamber is insensitive to the location of the RX inside the chamber. Fig. 4 represents the PDL of the 3D power chamber as a function of distance. When d lies between 1 and 15 cm, the maximum variation of the PDL is 6 mW for a nominal PDL of 100 mW. Such performance opens up opportunities to implement a wide variety of different wireless head mountable or implantable systems for small animal research.

The voltage regulator (Fig. 2) provides 3.3V to power up the MSP430. The output voltage of the regulator is reported in Fig. 5. There is no change in the regulated voltage when an angular misalignment of 30° of the receiver is performed, which promise excellent performance since rotation and angular misalignment of the receiver are unavoidable when working with freely moving animal. The proposed 3D power chamber is robust against receiver angular misalignments up to 80°, which cause a drop in the PDL of only 10% for the worst-case angular misalignment of 80°. These characteristics show the critical advantage of the proposed 3D power chamber for several applications in research with freely-moving animals.

The specifications of the presented system are summarized in Table I. The proposed wireless stimulator prototype 1) can drive 4 LEDs, 2) provides up to 70 mW of recovered power continuously, 3) has a power efficiency of the inductive link of 59%, 4) provides nearly constant power delivery in 3D, 5) is robust against angular misalignments of the receiver up to 80°, 6) features power localization [22], 7) and eases integration with several types of wireless head mountable research systems.

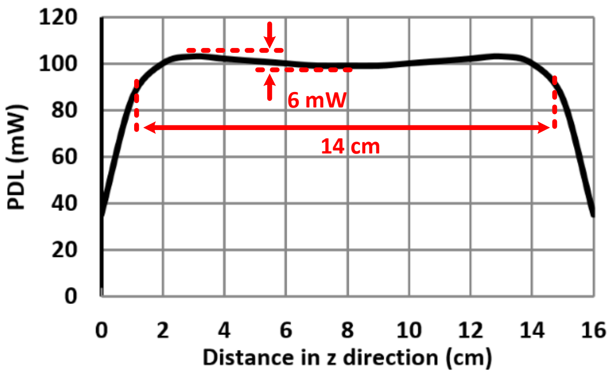


Fig. 4. Measure PDL to illustrate uniformity of the power delivery along z for the proposed power chamber.

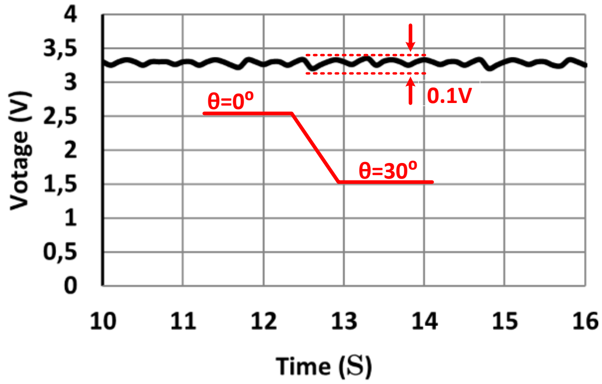


Fig. 5. Measured regulator output voltage as function of time while performing a 30-degree misalignment of the RX inside the 3D power chamber.

IV. CONCLUSION

This paper presented our recent progress towards the development of wireless optical stimulator system. The power chamber features uniform power distribution in 3D for continuously powering power-hungry optical components, which are widely utilized in optogenetic research. The power system provides a robust power delivery against subject movements in all x, y and z directions. Moreover, the PDL drops by only 10% for a maximum angular misalignment of 80° of the receiver, whereas there is no effect up to 30°. Therefore, our proposed prototype does not require a closed-loop power control system to maintain uniform power transmission along z. The proposed power chamber provides power localization that recruit a given subset of coils of the TX array to transmit power towards the receiver without using any additional detection circuitry. The measurement results have shown robust power-delivery inside the effective volume of the 3D power chamber. Moreover, the implemented prototype features several desirable characteristics that opens up opportunities for a wide variety of wireless head mountable/implantable systems for research with small freely moving animal models.

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