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

A Wireless and Batteryless Neural Headstage with Optical Stimulation and Electrophysiological Recording

Reza Ameli, *Student Member, IEEE,* Abdollah Mirbozorgi, *Student Member, IEEE,* Jean-Luc Néron, Yoan LeChasseur, Benoit Gosselin, *Member, IEEE*

***Abstract*— This paper presents a miniature Optogenetics headstage for wirelessly stimulating the brain of rodents with an implanted LED while recording electrophysiological data from a two-channel custom readout. The headstage is powered wirelessly using an inductive link, and is built using inexpensive commercial off-the-shelf electronic components, including a RF microcontroller and a printed antenna. This device has the capability to drive one light-stimulating LED and, at the same time, capture and send back neural signals recorded from two microelectrode readout channels. Light stimulation uses flexible patterns that allow for easy tuning of light intensity and stimulation periods. For driving the LED, a low-pass filtered digitally-generated PWM signal is employed for providing a flexible pulse generation method that alleviates the need for D/A converters. The proposed device can be powered wirelessly into an animal chamber using inductive energy transfer, which enables compact, light-weight and cost-effective smart animal research systems. The device dimensions are 15×25×17 mm; it weighs 7.4 grams and has a data transmission range of more than 2 meters. Different types of LEDs with different power consumptions can be used for this system. The power consumption of the system without the LED is 94.52 mW.**

I. Introduction

Optogenetics is a new experimental method that is revolutionizing neuroscience research by providing new means to inform the mechanisms and treatment of brain injury and disease based on light to selectively activate or silence specific cell types [1]. By introducing into neurons light-sensitive proteins that regulate the ion conductance of the membrane, optogenetics can achieve fast, spatially controlled and minimally invasive modulation of cellular activity in freely moving animals [2], [3]. In order, to be informative in an experimental setting, it has been pointed out that optical stimulation should be tightly coupled with an appropriate quantitative readout to map out the functional connectivity of interrogated groups of neurons [4]. Indeed, such combination of optical control and electrical recording holds substantial potential for clinical applications such as aetiology and treatment of several diseases, like Parkinson's disease, epilepsy, depression, obsessive-compulsive disorders and chronic pain [1]. Presently, different commercial products provide researchers with rather comprehensive neural recording and stimulation capabilities. Such products include multi-channel recording and multi-channel stimulation devices [5], [6]. Alongside with commercial products, researchers have been developing new tools for neural research [7], [8], [9], [10]. While presently available optogenetic setups use stimulating light and recording electronics tethered to a power source, small wireless electronic headstages have been proposed for conducting experiments with freely moving animals [7]. To our knowledge, a wireless device that can stimulate neurons optically and record neural activities at the same time is not presently available [5], [11]. Indeed, the significant amount of power drained from the stimulating LED and electronics, combined with the need for a light-weight device that can be mounted atop of the head of small rodents set very challenging requirements on such design.

This work proposes a wirelessly powered headstage design that centers around a super-capacitor and a high-efficiency resonant power transfer system [12], [13]. The device, not requiring any batteries, is powered using a 4-coil inductive link and is capable of simulating the brain using a fiber optic-connected LED. It incorporates a low-power off-the-shelf wireless microcontroller [14] operating in the 868 MHz band and providing a data rate of up to 320 Kbit/s for controlling the LED and enabling bidirectional communications with a base station. Such wireless microcontroller allows end-users to wirelessly configure the headstage and receive the captured electrophysiological data from the two A/D channels. Section II of this paper gives an overview of the proposed system and describes each of its building blocks in detail. Section III presents the bench-top measurement results carried out with the headstage, and section IV concludes this paper and gives an outlook for future work.

II. System Design

Fig. 1 shows a simplified block diagram of the proposed headstage device. The headstage consists of three stacked printed circuit boards (PCB) that divide the functionality of the system into three main blocks: 1) a two-channel electrophysiological signal readout circuitry, 2) a power management unit (PMU), and 3) a low-power RF microcontroller (MCU). An optic fiber connected to a LED is used for illumination of target neurons, while two microelectrodes are used for electrophysiological recording. The optical fiber-connected LED is mounted side by side with the microelectrodes and connected to the analog readout circuitry and the LED driver circuitry, respectively, using a small-footprint connector. The PMU includes a DC-DC converter to power up different building blocks, a LED driver and a super capacitor that acts as a power source for the whole system. The system uses a small folded microstrip spiral antenna [15] to communicate with a base station. Light stimulation pattern plays an important role in

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. R. Ameli, A. Mirbozorgi and B. Gosselin are with the Dept. of Electrical and Computer Eng., Université Laval, Quebec, QC G1V 0A6, Canada (e-mail: benoit.gosselin@gel.ulaval.ca). J.-L. Néron, and Y. LeChasseur are with Doric Lenses Inc., Quebec, QC G1P 4N7, Canada (e-mail: jluc@doriclenses.com)

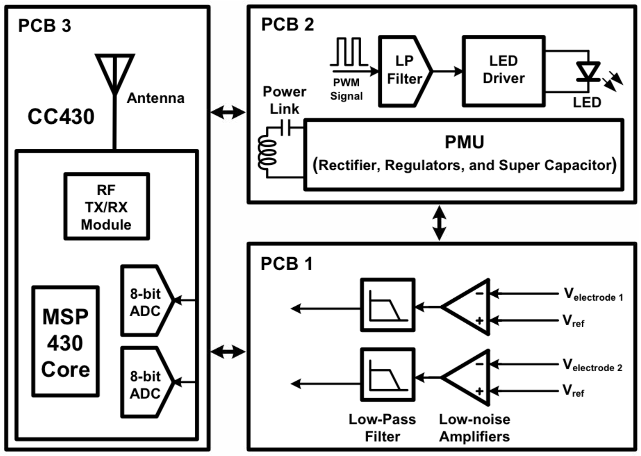

Figure 1. Block diagram of proposed wireless optical headstage.

activation and silencing the neurons. The LED has maximum forward currents (I_{LED}) of 95 mA. The system can be programmed to generate the required stimulation patterns by changing the pulse width, period and current amplitude of the optical stimulation LED. This configuration is done by wirelessly conveying the stimulation parameters into the MCU. After configuring and starting the device, an end-user can see the recorded electrophysiological signals at the base station and in real-time. Generally, in order to control the LED driver circuitry a D/A converter is required. However, in this design, the DAC functionality is implemented programmatically using a low-pass filter and PWM signals that are digitally generated by the RF microcontroller, which avoids adding extra integrated circuits. This configuration results in lower integrated circuits count, decreased total cost, smaller size and lower power consumption.

A. Light Stimulating Patterns

The proposed headstage allows two different patterns for controlling the LED: *constant mode* and *periodic mode*. In constant mode, the LED is constantly active and direct current passes through it, so the brain cells are actuated in a constant manner. In periodic mode, the LED is turned on and off periodically, and the rate (f_P) and the duty cycle (D_{fP}) of this toggling can be specified by the end-user. The toggling rate (f_P) can vary from 0.4 Hz to 1 kHz and the duty cycle (D_{fP}) can be selected from 10% to 90%. In both constant and periodic modes, the light intensity can be adjusted. Fig. 2 shows the light stimulation circuitry. The light intensity is proportional to the LED current that is in turn directly proportional to the voltage of the base of the transistor in the LED driver circuit. In order to adjust the base voltage of the driver transistor, the desired light stimulation pattern masks a PWM signal with constant period and variable duty cycle. The duty cycle of this PWM signal determines the voltage on the base of the transistor. Thus, the digital microcontroller output is a PWM signal masked with a stimulation pattern of predetermined pulse width and frequency. The microcontroller output is passed through a low-pass filter that passes the mask (stimulation pattern) but filters the PWM signal. As a result, the voltage on the transistor base and the LED current follow the stimulation pattern, and their amplitudes are proportional to the duty cycle of the PWM signal. The PWM signal that

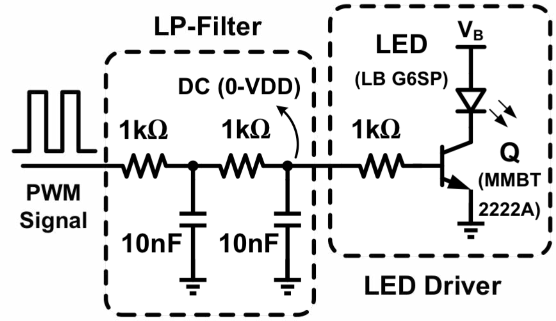

Figure 2. LED control strategy.

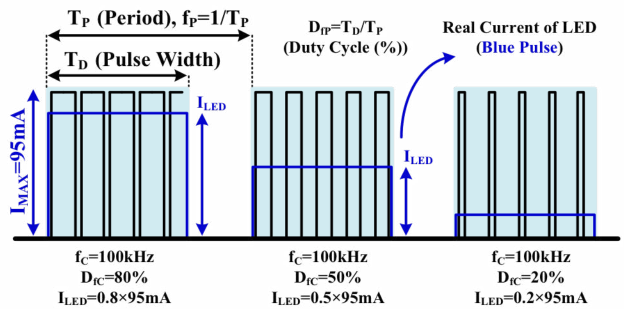

Figure 3. LED control strategy using PWM and low-pass filter.

determines the light intensity changes much faster than the stimulating pattern and its duty cycle ranges from 10% to 90%, which corresponds to a LED current of 5 to 95 mA. Fig. 3 shows the PWM signal that is fed to the low-pass filter input, and the resulting LED current for three different duty cycle values of the PWM signal. If the microcontroller that produces these signals is powered by a 3.3 V source, it can be shown that properly filtering a 50%-duty cycle PWM signal gives a 1.65V-DC voltage. Since the relationship between the amplitude of the filtered PWM and the duty cycle is linear, a wide range of voltages are produced using this method. For filtering the microcontroller output, a second order low-pass RC network is used. Fig 2 shows such network. The values of the resistor and the capacitor have been selected to let the filter pass the stimulation pattern, but not the PWM signal. The transistor that is connected to the LED, converts the output of the low-pass filter to the LED current. Since the transistor is always in the active region, variation of duty cycle of PWM signal has an almost linear relationship with the LED current level. This is verified by measurement results is Section III. Furthermore, this allows tuning the LED current at any desired level.

B. Readout Interface

The data acquisition (DAQ) system consists of two parts: 1) an analog readout, and 2) digitization. The analog readout section consists of two identical signal conditioning circuits. Each of which comprises a low noise amplifier (LNA), a DC suppressor, a low-pass filter and a variable gain amplifier (VGA). The input of each channel is connected to the output of one of the microelectrodes. Fig. 4 depicts the analog readout interface circuit. The channels are connected to a multi-input analog-to-digital (A/D) converter available in the

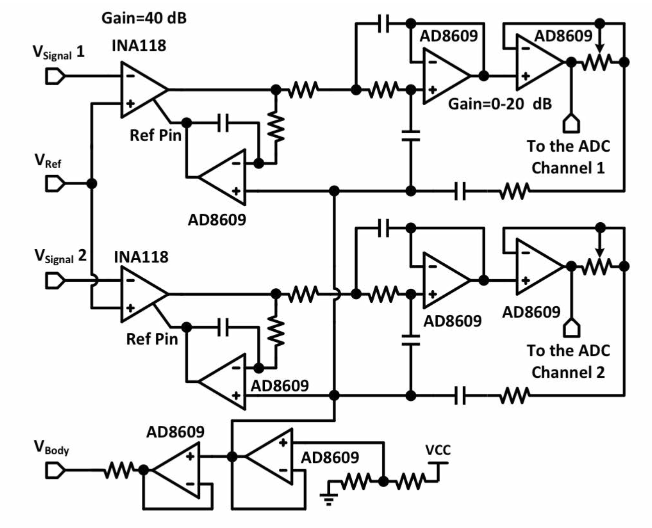

Figure 4. Two-channel analog readout circuitry.

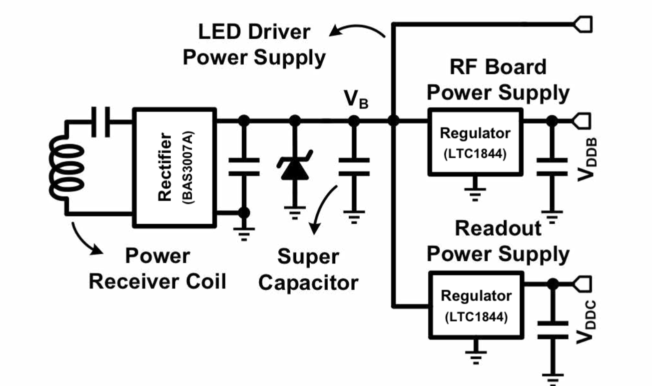

Figure 5. PMU block diagram.

RF microcontroller. Quantization resolution is 8 bits. The neural signals are digitized at 20,000 samples/sec in each channel, and sent back to the base station afterwards, using the RF link.

C. Power Management Unit

The power management unit powers up the whole system including the RF microcontroller, the LED driver and the readout circuitry, for a power transmission range within 7 cm between the transmitter and headstage. It is part of a 4-coil power transmitter inductive link and includes a rectifier, a Zener diode high voltage protector, a super capacitor and voltage regulators (3.3V). The super capacitor is the main source of power. The stimulating LED current is supplied directly by the super capacitor (V_B) as shown in Figure 5. This avoids wasting any power in the regulator since output current and voltage drop of the regulator can be very high (95 mA and 0.7V respectively). Additionally, a higher voltage at the BJT collector makes the LED switching easier. The schematic of the PMU is shown in Figure 5. It should be noted that, since the LED is directly connected to the super capacitor, switching-noise effect on the power supply voltage or other parts is negligible. Moreover, in order to avoid any switching noise in the readout circuitry, two regulators have been utilized to separate the power supplies of the RF microcontroller from the readout analog section. The PMU also includes capacitors for tuning the power receiver coil in the predefined carrier frequency, and eliminating the power supply ripples and any high frequency noise. Specifications of the power transmission link are included in Table 2 in Section III.

TABLE I. CHARACTERISTICS OF LED STIMULATION SIGNAL.

Parameter	Measured values
Number of stimulation channels	1
Pattern frequency (f_P)	0.4 Hz < f_P < 1 KHz
Pattern duty cycle (T_D)	10% < T_D < 90%
Worst case pattern duty cycle step (T_D)	5%
LED current (I_{LED})	5 mA < I_{LED} < 95 mA
LED current ripple	2 mA <
Fast PWM frequency (f_C)	100 KHz
Fast PWM duty cycle (D_{fC})	10% < D_{fC} < 90%

D. Control and Data Transmission

DAQ, digitization, RF communications and generation of LED stimulation patterns are controlled by a Texas Instruments RF microcontroller (CC430F6137) [14]. Among others, its duties include: 1) sending the acquired signals back to the base station, and 2) sourcing the LED stimulation patterns. A printed antenna with a small footprint has been used to decrease the headstage dimensions.

III. MEASUREMENT RESULTS

This section reports the measured characteristics of the headstage. In order to test the system, an arbitrary waveform generator has been used to generate synthetic test neural signals, and the headstage is powered wirelessly, without battery, using an inductive link (Section II.C). The analog readout gain was set to 100 V/V. Fig. 6 shows the wirelessly powered headstage, including the stimulation LED, the optical fiber and microelectrodes. Also included in Figure 6 are the arbitrary signal generator and the received synthetic signal (from one channel) in the base station computer. Table 1 summarizes the parameters of the stimulation signal and Table 2 summarizes the measured values of the system. The measured relation between the duty cycle of the PWM signal and the stimulation LED current is depicted in Figure 7. This relationship is almost linear and the nonlinearity at the left side of the curve is due to the nonlinear nature of the transistor. Moreover, any nonlinearity can be compensated digitally using the MCU or in the base station computer. Fig. 8 demonstrates relative power consumption of different blocks of the system in a pie chart while the average power for the LED has been shown. Most of the power consumption is due to the LED which can be replaced by smaller and less power-hungry LEDs [16].

IV. CONCLUSION

In this paper we presented a new optogenetics research device that is wirelessly powered, can stimulate neurons using light, and is capable of capturing and wirelessly transmitting the data from two neural recording channels. The sampling rate of each channel is 20,000 samples/second and the A/D precision is 8 bits. Future improvements of this device consist of adding DSP capabilities such as real-time spike sorting to lower data transmission rate as well as power consumption, so more recording channels can be implemented. Moreover, we seek to increase power efficiency in the PMU in order to increase the number of optical stimulation channels. Last but not least, the size and

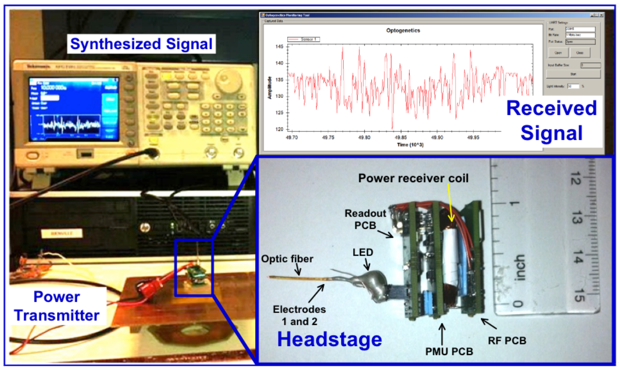

Figure 6. Complete system setup including the headstage, power transmitter, an arbitrary waveform generator and the base station control panel.

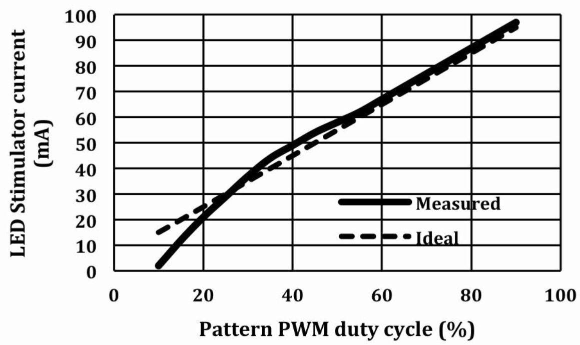

Figure 7. LED current as a function of PWM duty cycle, measured to verify the linearity.

TABLE II. HEADSTAGE CHARACTERISTICS (MEASURED RESULTS).

Parameter	Value
Weight	7.4 grams
Dimensions	15×25×17 mm
Supply voltage	3 V
Readout circuitry power consumption	3.73 mW
PMU power consumption	16.54 mW
RF microcontroller power consumption	74.25 mW
LED power consumption (constant mode)	(20 - 380) mW
Total power consumption (constant mode)	(114.52 – 474.52) mW
RF Operating frequency	868 MHz
Data transmission range	> 2m
RF output power	0 dBm
Data rate	320 Kbits/second
Modulation	GMSK
Inductive link structure	4-coil inductive link
Power carrier frequency	1 MHz
Power transmission range	< 7 cm
Type of coils	Wire-wound
Number of recording channels	2
Input referred noise	1 µVrms
Sampling frequency (for each channel)	20,000 sample/second
ADC precision	8 bits
Readout interface gain	40 to 60 dB
Readout interface CMRR	> 100 dB
Readout interface bandwidth	100 Hz to 10 KHz

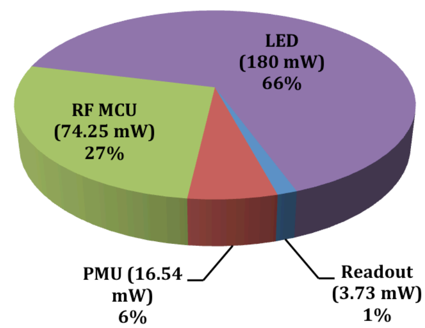

Figure 8. Relative power consumption of different system blocks with average LED power consumption.

physical shape of the device will be greatly decreased trough the use of smaller off-the-shelf component packages as well as custom integrated circuits, so the risk of hazards (for both the animal and the device) will be minimized during *in vivo* experiments.

REFERENCES

[1] K. Deisseroth, "Optogenetics," *Nat Meth,* vol. 8, pp. 26-29, 2011.

[2] E. S. Boyden, F. Zhang, E. Bamberg, G. Nagel, and K. Deisseroth, "Millisecond-timescale, genetically targeted optical control of neural activity," *Nat Neurosci,* vol. 8, pp. 1263-1268, 2005.

[3] D. Huber, L. Petreanu, N. Ghitani, S. Ranade, T. Hromadka, Z. Mainen, and K. Svoboda, "Sparse optical microstimulation in barrel cortex drives learned behaviour in freely moving mice," *Nature,* vol. 451, pp. 61-64, 2008.

[4] F. Zhang, A. M. Aravanis, A. Adamantidis, L. de Lecea, and K. Deisseroth, "Circuit-breakers: optical technologies for probing neural signals and systems," *Nat Rev Neurosci,* vol. 8, pp. 577-581, 2007.

[5] Triangle biosystems Inc. [Online]. Available: http://www.trianglebiosystems.com/

[6] Blackrock Microsystems. [Online]. Available: http://www.blackrockmicro.com/

[7] C. T. Wentz et al, "A wirelessly powered and controlled device for optical neural control of freely-behaving animals," *Journal of Neural Engineering,* vol. 8, no. 4, 2011.

[8] Arfin, S. K., M. A. Long, M. S. Fee, and R. Sarpeshkar. "Wireless Neural Stimulation in Freely Behaving Small Animals." *Journal of Neurophysiology,* vol. 102, no. 1, pp. 598-605, 2009.

[9] Degenaar, P et al. "Individually addressable optoelectronic arrays for optogenetic neural stimulation," in the *IEEE Biomedical Circuits and Systems Conference,* (BIOCAS'10), pp. 170 – 173, 2010.

[10] J. G. Bernstein and E. S. Boyden, "Optogenetic tools for analyzing the neural circuits of behavior," *Trends in Cognitive Science,* vol. 15, pp. 592–600, December 2011.

[11] Kendall Research Systems. [Online]. Available: http://kendallresearchsys.com/

[12] 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, pp. 579-591, 2011

[13] A. K. RamRakhyani, S. Mirabbasi, and C. Mu, "Design and Optimization of Resonance-Based Efficient Wireless Power Delivery Systems for Biomedical Implants," *IEEE Transactions on Biomedical Circuits and Systems,* vol. 5, pp. 48-63, 2011.

[14] MSP430 SoC With RF Core. [Online]. Available: http://www.ti.com/product/cc430f6137

[15] Compact 868/915 MHz Antenna Design. [Online]. Available: http://www.ti.com/lit/an/swra160b/swra160b.pdf

[16] H. Cao, L. Gu, S. K. Mohanty, J.-C. Chiao, "An Integrated µLED Optrode for Optogenetic Stimulation and Electrical Recording," *IEEE Trans. on Biomedical Engineering*, vol. 60, no. 1, January 2013.