A Compact Wireless Headstage based Optogenetic Neuromodulation and 32-channel Electrophysiological Recording System

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***Abstract*—This paper demonstrates a commercial off-the-shelf components (COTS)-based miniaturized wireless optogenetic headstage with simultaneous optical stimulation and electrophysiological recording capability for freely moving rodents. The proposed headstage contains 32 recording channels. The optical stimulation system is a battery-powered neural stimulator, comprised of a low dropout regulator (LDO), an oscillator, and a μLED. The electrophysiological signal recording system includes an intracortical neural probe made of a GaN-on-silicon substrate, an array of neural amplifiers with an integrated analog-to-digital converter (ADC), a transceiver integrated circuit, and a ceramic antenna. The integrated MUX with the ADC allows sampling of the amplified voltage at a sampling rate of 4000 kSamples/s. By placing the headstage on the head of a rodent and recording the neural signals from the Ventral Tegmental area of the brain, the system is experimentally validated in *in-vivo*. Experimental result shows that the proposed headstage can trigger neuron activity while collecting and detecting single-cell microvolt amplitude activity from multiple channels.**

***Index Terms*—electrophysiology, optical stimulation, optogenetic, transceiver.**

I. Introduction

Developments in miniaturized implantable medical devices are playing important roles to the treatment of numerous neurological disorders [1],[2]. Manipulation of the neuron activity via stimulation can be utilized to treat different neural diseases, like Parkinson's disease, chronic pain, epilepsy etc. [3]. Optogenetic stimulation is an effective neuromodulation stimulation technology that can be applied to accurately excite particular types of neurons, as compared to traditional electrical or magnetic stimulation [4]. Genetically modified neurons can be optically stimulated to examine and control numerous neural functions by using optogenetic neuromodulation [5]. An optogenetic neuromodulation system generally incorporates electrophysiological recording and optical stimulation modules for conducting closed-loop neuromodulation to control neural activities in certain locations of the brain.

Generally, the electrophysical recording system contains neural electrodes, amplifiers, multiplexer (MUX), an analog-to-digital converter (ADC), transceiver, and a ceramic antenna. There are two main constraints while implementing a wireless headstage capable of simultaneous stimulation and recording from multiple channels: the limited power resource and small form factor. In this paper, low-power analog circuitry

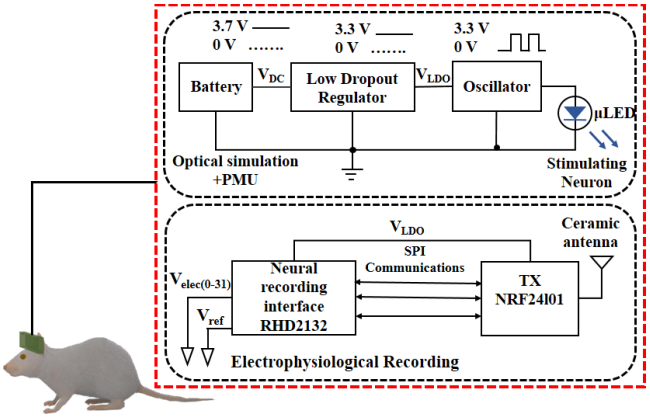

Fig. 1. Block Diagram of proposed 32-channel wireless recording and optogenetic stimulation system

implemented with standard commercial off-the-shelf (COTS) components is presented. The overview of the system is presented in Fig. 1. The amplifier chip for recording the neural signal (RHD2132 by Intan) in the proposed system has a built-in 16-bit ADC to convert the amplified analog signals into digital bits. The neural signals are transmitted to a remote receiver by a sub-2.4 GHz radio transceiver (NRF24l01) by Nordic Semiconductors integrated with an MSP430 microcontroller (MCU) for further processing. In this work, only two chips has been used and thus a small form factor is achieved, while the power budget is also maintained and the electrophysiological signal is recorded precisely and accurately. Experimental results show the system's feasibility recording the neural signals from 32 channels and the wireless data transmission. The rat head-mounted headstage system's capacity to perform battery-powered, reconfigurable optogenetic stimulation is also demonstrated in this paper.

In our previous design, the μLED and the recording electrodes were separate, thus, the electrophysiological signal couldn't be recorded from the same neuron. The sampling rate was lower and the power consumption rate was higher in the previous prototype. In this proposed system, the limitations of the previous system have been allevated. The μLED and the recording electrodes are placed in the same shank which enables the system to detect cellular-level performance. The

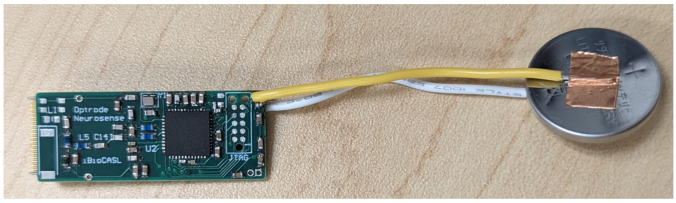

Fig. 2. The Optrode Neurosense Recording Interface with the Lithium-ion battery

TABLE I
CHARACTERISTICS OF THE SYSTEM

Parameter	Value
Number of recording channels	32
ADC resolution (bits)	16
Sampling rate (kSamples/s)	4000
Transceiver frequency band	2.4 GHz
Power consumpsion	178.2 mW
Battery Life	77 min

sampling rate is higher in this proposed system.

II. System Overview

Fig. 1. represents the block diagram of the optogenetic headstage that is proposed in this work. The headstage is completely developed using commercially available components. The complete system consists of two parts that are interconnected. The first part contains a printed circuit board (PCB), which incorporates electronics for collecting data, wireless data transfer, and optical stimulation. The next portion is an implanted module that can be detached and contains both the neural probe and the μLED. The characteristics of the proposed system are presented in Table I.

A. Implantable Neural Probe

In this system, a 32-electrodes probe has been implemented as a connection between the genetically modified neurons and the electrophysical recording circuitry. The optoelectrodes that has been used in the proposed system, are manufactured from the Yoon Lab of University of Michigan. The optoelectrodes are fabricated on a GaN-on-silicon substrate with recording sites and precisely defined µLED-12-32-As (10 x 15 µm), which allows simultaneous neural signal recording and optogenetic stimulation with <50 µV_{pk-pk} stimulation artifact.

B. Electrophysical Recording Module

The neural signal recording interface enables conditioning and sampling of both local field potentials and low-amplitude extracellular action potentials. For action potentials (APs), the frequency range of the brain signals is found between 300 Hz and 5 kHz [6], while for local field potentials, it is found between 0.5 Hz and 200 Hz [7].

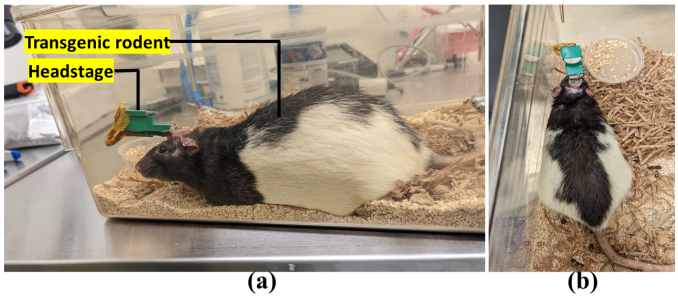

Fig. 3. (a) Side view and (b) Top view In-vivo experimental setup: transgenic rat with the headstage mounted on its head

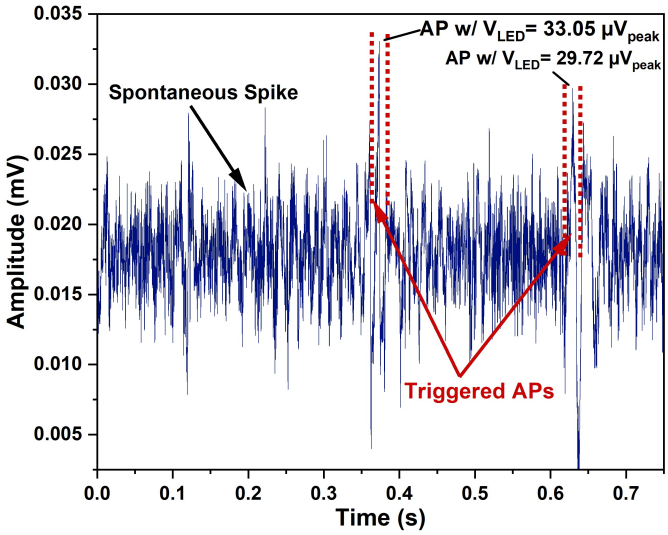

Fig. 4. Wirelessly recorded spontaneous neural activity.

C. Wireless Transceiver

The neural data has been transferred to a base station via a NRF24l01 radio transceiver by Nordic Semiconductors, which is also used to receive the optical stimulation parameters. This radio transceiver operates in the 2.4-GHz center frequency of the industrial, scientific, and medical (ISM) band. It can operate with baud rates from 250 kbps up to 2 Mbps. The NRF24L01 Module can both transmit and receive the data. It uses Serial Peripheral Interface (SPI) protocol for communicating with microcontrollers. With this commercial transceiver, a low-power operation is possible. The receiver module is linked to the computer, where the LabVIEW Graphical User Interface (GUI) is used to reconstruct and process the data. Intan RHD2132 amplifier board has been used to record from the 32 electrodes.

D. Power Management Unit

The power management unit (PMU) comprises a 3.7 V EEMB LIR2032 Lithium-ion battery which has 45 mAh capacity to supply power to the electrophysical recording and stimulation system. The 3.7 V voltage from the battery is reduced to 3.3 V using a TPS746-Q1 ultra low power low-dropout voltage regulator (LDO) by Texas Instruments since the recording system needs a constant 3.3 V supply. Moreover, a pulse stimulation with constant light intensity is needed for neuronal stimulation. In order to deliver the pulse stimulation

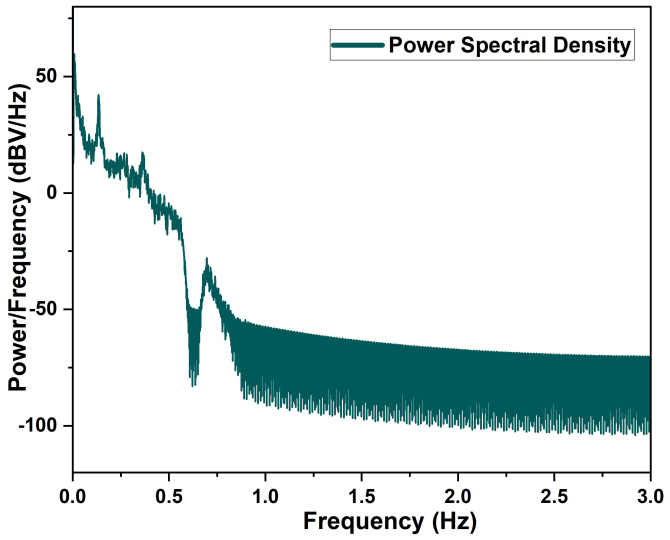

Fig. 5. Power Spectral Density of the recorded neural signal

with a constant 3.3 V amplitude, an oscillator circuit is implemented following the LDO circuit. A commercially available Microchip MIC1555 CMOS RC oscillator is incorporated into the neural stimulation circuit to deliver pulses with a specific frequency to the μLED.

E. 3D-printed Headstage

A 3D-printed rectangular headstage of 3.5 cm $\times$ 1.4 cm $\times$ 1.1 cm dimension which contains three slots to carry the PMU (coin cell), the neural stimulation circuit and the recording interface board. The Polylactic acid (PLA) filament of 1.75 mm are used to create the headstage in the Creality Ender3 3D printer .

III. Implementation and Measurement Results

The wireless recording circuitry and the stimulation LED are both powered by 3.3 V from a Lithium-ion battery of 3.7 V by the PMU circuit. The optical stimulation and neural recording systems are both included on the rigid four-layer PCB board on which the headstage is mounted. The transceiver and ceramic antenna is placed in the bottom layer of the recording board, while the top layer is designated for the amplifier. The implantable neural probe and the headstage are connected by an Omnetics connector in the top part, which is used to interface with the optrode. The neural probe contains the implantable shank. The synthetic neural spike signals are applied to the neural probe and transmitted wirelessly. The optrode neurosense recording PCB board is represented in Fig. 2.

A transgenic female mouse (Long Evans rat (Charles River)) has been used to record/stimulate from the brain surface. The rat's Ventral Tegmental Area was the location of the optrode's stereotaxic implantation. Blurr holes were created by using a stereotaxically placed drill for the insertion of the optrode and bone screws. The rat with the headstage installed on top of it is depicted in Fig.2. As soon as the animal woke up after the surgery, the first test was performed. The battery contact from the uncovered portion of the implant was taped while the animal was being tested. The animal was allowed to move freely for the measurement. Fig. 3 shows the experimental set-up for *in-vivo* measurement. The headstage has been mounted on the head of the freely moving transgenic rodent.

TABLE II
Comparison of performances with the state of-the-arts

Parameters	[4]	[8]	[9]	This work
Number of electrophysical recording channels	32	32	32	32
ADC resolution (bits)	16	16	16	16
Sampling rate (kSamples/s)	20	20	-	4000
Wireless transmission capability	Yes	Yes	No	Yes
Power consumption (mW)	175	122.1	-	178.2
Neural electrode impedance (Ω)	-	-	10-500k	100 - 1500k

The wireless transceiver transmits the recorded neural signal at a transmission power of 0 dBm. The actual detected spikes and shapes are obtained from the generated neural signal. The headstage can detect the AP (Action Potential) waveforms. Fig. 4 shows the neural activity measured by optroelectrode when the light pulses were delivered to the neurons of the animal's brain. A stable and clear optical-induced neural activity has been observed in APs in time domain. Experimental results show that the proposed headstage is capable off collecting and transmitting single-spike events evoked by optical activation. From the spontaneous spike, the triggered AP values are in the range of 33.05 μV and 29.72 μV. The power spectral density of the recorded neural signal is shown in Fig. 5. The comparison of performances with the states-of-the-arts is shown in Table II. The proposed architecture is able to achieve maximum sampling rate with 32 channels compared to the other systems.

IV. Conclusion

The complete electrophysiological recording system and optical stimulation system, which can record neural signal using a 32-channel neural probe, are presented in this study. The proposed headstage is capable of activating the neurons using light pulses which is generated by the 12 μLEDs (3 per shank), and simultaneously collecting the neural signals from 32 recording channels. The results obtained from the measurement represent that the system module can detect the action potential. The proposed headstage has been experimentally validated *in-vivo* using optrode that is implanted into the brain of a transgenic rat. The whole system successfully collected and transmitted the neural activities.

Acknowledgment

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