Lightweight and Battery-less Multichannel Wireless Sensor for Swine Biopotential Recording

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***Abstract*— Continuous neural recording provides vital information to map the focus of seizures in epilepsy patients. For the first time, we validate our novel packaged battery-free and multichannel wireless neurosensing system (mWiNS) in large animals (swine). The implant is miniaturized by employing a multilayer 3D printed design that includes a shorting pin to reduce antenna size by ~50%. Measurements indicate reliable recovery of neural signals, demonstrating the capabilities of our proposed wireless system in recording neural epilepsy indicators.**

Keywords*— neural recorder, backscattering, implantable, wireless, battery-free, multi-channel.

I. Introduction

Approximately 3.4 million people in US are affected by epilepsy [1]. While medication is the first line of treatment for epilepsy patients, 30% of patients suffer from drug resistant epilepsy [1]. For these patients, surgical resection is usually the next step in treatment. This requires accurate mapping of the seizure onset zone (SOZ). Intracranial monitoring remains the gold standard for mapping the SOZ. However, existing systems for neural recordings consist of electrocortigraphic (ECoG) or stereo encephalographic (sEEG) electrodes protruding from scalp wired to stationary recording equipment. This exposes the patient to increased risk of pain, infection and hemorrhage, as well as a long, costly hospital stays (up to two weeks).

To address these limitations, our team developed a first of a kind implantable device to record neural activation in a wireless and fully passive manner. Recently, WiNS was enhanced with a multichannel design and an impedance matching circuit to address mismatches between electrodes and the recording circuitry [2], [3]. Several benchtop and *in vivo* measurements in Wistar Rats were performed to demonstrate the performance of WiNS [4]. However, the recorder remained prohibitively large due to its antenna size and associated impedance matching circuits. Therefore, measurements were performed in rats by placing the electrodes in the rat's brain and using a fabricated skin phantom between the implant and interrogator. In this paper, we present measurements using our newly developed and much smaller packaged implant in a larger animal model (swine). The implant was connected to an ECoG array, and the entire package was fully implanted using a sterile surgical procedure and while the pig was in sedation. After recovering, the animal was completely mobile and free of protruding wires with our implanted passive recorder. To test the implant, the swine limbs were stimulated, and somatosensory evoked potentials (SSEPs) were recorded. That is, our presented recordings and results demonstrate functional validation of our novel packaged, miniaturized multichannel recorder while performing *in-vivo* measurements.

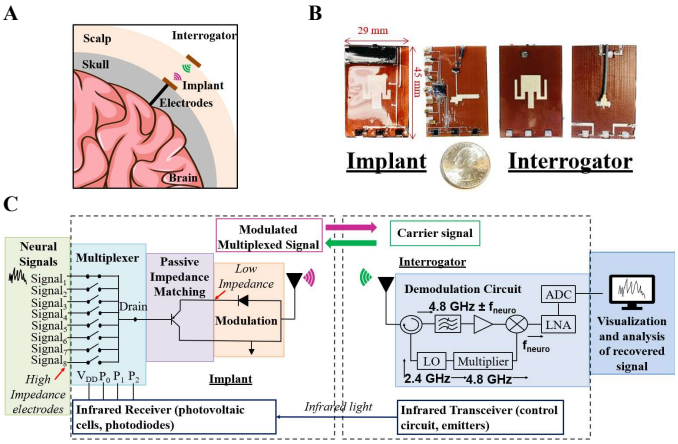

Figure 1. mWiNS set up and its major components. A) Schematic recording configuration showing the positioning of the electrode, implant and interrogator; B) Fabricated implant and interrogator; C) Block diagram of proposed system.

II. Neurosensing System

The multichannel wireless neurosensing system (mWiNS) is comprised of two principal components: the implant and the interrogator, as shown in Fig. 1. The operation of the proposed technology relies on radiofrequency (RF) and optical communication links. Notably, the incoming RF signal from the interrogator charges a capacitor in the implant that serves to power the implant circuitry and modulator. The implanted sensor is coated with a PDMS polymer for biocompatibility and connected to FDA-approved electrodes (ECoG). Also, the implant and interrogator employ well-matched dual-band antennas for near-field communication through skin.

For recording, the interrogator transmits a carrier excitation signal received by the implant antenna. This excitation signal is then mixed with the detected neural signals in the shown diode (modulator circuit) as in Fig. 1. Subsequently, the modulated signal is backscattered/transmitted towards the interrogator for demodulation, demultiplexing and processing, Notably, the optical components of WiNS are used for channel multiplexing. Specifically, multiplexing is carried out using a photovoltaic (PV) cell and 3 photodiodes (PDs) incorporated into the implant. Additionally, the interrogator is equipped with 4 light emitting diodes (LEDs). One of the LEDs is used to communicate with the PV cell, with the remaining three used to trigger the appropriate LEDs within the implant. The power output of the PV cell provides a stable power source for the multiplexer with the potential to reverse the bias of the PDs. Notably, the output

(code) of the 3 PDs is used for channel selection. The LEDs can be activated using a power supply via a microcontroller for automatic control. As such, the maximum sampling rate of ~10 kHz per channel is achieved. This sampling rate allows the recording of both normal and epileptic neural signals generated in the brain.

The implant and interrogator were designed and fabricated using a multilayered 3D printing approach, leading to a 52% smaller footprint as compared to the design in [4]. This implant was composed of 2 layers of acrylate-based polymer ($\varepsilon_r = 2.8, \tan\delta = 0.02$) and 3 layers of silver conductive ink. The fabricated implant and interrogator are depicted in Fig. 1B. A comparison with other implants in terms of size, power sources and power consumption is provided in Table I.

TABLE I. COMPARISON WITH STATE OF THE ART.

	This work	Ref. [5]	Ref. [6]
Size	45x30x3 mm^3	59x38x15 mm^3	19x19x30 mm^3
Weight	5 g	56 g	5.7 g
No. channel	8	4	32
Power source	RF (2.4 GHz) & PV cell	Battery (90 days life)	Inductive (13.56MHz)
Power Cons.	98 µW		35mW

III. Swine Data Collection Methods and Procedures

A. Animal Preparation

All animal procedures were approved and performed by the Institutional Animal Care and Use Committee (IACUC) at Florida International University (Approval No. 23–023). The data in this paper were obtained from experiments performed in a female swine. For this experiment, an Ag/AgCl probe was fabricated for implantation using an electrochemically coated silver wire. Also, for multichannel data, an ECoG array (8 channels, FDA approved) from AD-Tech Medical Instruments Corporation was employed. The implant and ECoG array were placed following a craniotomy at the cortex, targeting the brain region that detects somatosensation (see Fig. 2A). The Ag/AgCl probe served as the electrical ground connected to a screw in the skull. Initial recordings were performed under anesthesia. Also, two small needle electrodes (gauge 26, 1" length) were inserted in the pig's hindlimb to provide electrical pulses. These were generated using an isolated pulse stimulator (AM Systems Model 4100) having a current amplitude of 5-35 mA at 2 Hz with a negative pulse 200 µs in time width.

B. Neural Activity Recordings

For the first time, this paper evaluated the somatosensory of evoked potentials (SSEPs) recordings from swine. The raw data from the hindlimb stimulation were filtered using a 60 Hz notch filter and band-passed across 0.1-100 Hz. Additionally, SSEPs from 8 channels were analyzed after digitizing the demodulated dataset at a sampling rate of 500 Hz per channel. Each recording (2min) was segmented from -50 to 250 ms and referenced to the time of stimulus onset. Subsequently, SSEPs were extracted by averaging across the signal segments. Fig. 2B shows the comparison between the 8-channel SSEPs (left) and the control signal (right). The control signal refers to the average of the recordings with no stimulation. This study clearly shows that our proposed recording system is capable of detecting normal, evoked neural signals.

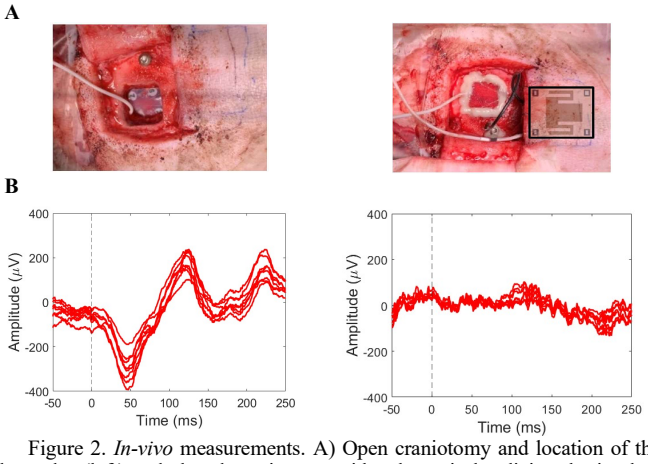

Figure 2. *In-vivo* measurements. A) Open craniotomy and location of the electrodes (left) and closed craniotomy with schematic localizing the implant (right); B) Evoked potential from an 8-channel (left) recording in response to hind limb stimulation (grey dashed line). There are notable responses at approximately 50 and 150ms, as compared to no response without stimulation (control signal, right).

IV. Concluding Remarks

A unique 3D additively manufactured neural recorder with 52% size reduction as compared to previous recorders was presented. For the first time, SSEPs were recorded *in vivo*, from a sedated swine using our battery-less implant, demonstrating a cutting edge capability. Future work will focus on epilepsy recordings from pigs in their normal environment.

Acknowledgment

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