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

An Electroacoustic Recording Device for Wireless Sensing of Neural Signals*

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***Abstract*—Elimination of wires connecting neural recording electrodes to external electronics is highly desired, particularly in survival animal studies, due to neural damage and the device failures caused by these wires. In this study, an electroacoustic device for sensing and wireless transmission of neural signals to an external unit is proposed and results from a prototype are presented. In this method, the neural signals modulate the acoustic pulse amplitudes generated by a small piezoelectric element that is implanted at the recording site. The acoustics waves are detected wirelessly outside the nervous system by another piezoelectric transducer and the neural signals are extracted by amplitude demodulation. To test the prototype, a sinusoidal signal with 100μVpp amplitude was applied in phosphate buffered saline to simulated neural signals and the external transducer was placed 10mm away from the recording element. The results show that a sinusoidal signal of the given amplitude could be wirelessly sensed and reconstructed with a signal-to-noise ratio of 14dB.**

Key Words: **neural recording, remote sensing, ultrasound.**

I. INTRODUCTION

Electrical activity of neural cells can provide fundamental information about their function as a part of a larger network when recorded in a behavioral context. Non-invasive approaches such as the electroencephalogram (EEG) can provide this information with limited temporal and spatial resolution. Neural recordings with electrodes implanted in the brain parenchyma can sample neural activity at spatial scales ranging from single cells to networks of cell assemblies, which is called multi-unit activity. Many research laboratories have utilized implantable sub millimeter-scale recording probes that allowed long-term and stable recordings of neural signals from the central nervous system [1-3].

Most modern neural recording systems require a wired connection from implanted electrodes to external amplifiers and recorders. This physical connection presents two major problems: 1) the connecting wires generate tethering forces on the electrodes and cause neural damage; 2) the wires limit the longevity of the system due to breakages and failure to record [1, 3, 4]. To eliminate these problems, neural signals from the implanted electrodes should be transmitted to a unit outside the nervous system, or the body, wirelessly. The main objective of this study was to design an implantable neural recording device that can remotely transmit the signals to an external unit by utilizing the unique properties of piezoelectric materials. A single-ended amplifier with two stages was designed to amplify the neural signals first. A third stage was used to amplitude modulate the electro-mechanical ringing of a piezoelectric element with the neural signals. The acoustic waves generated by the piezoelectric element were detected by an ultrasonic transducer and demodulated to reconstruct the original signal. The results show that a sinusoidal signal with comparable amplitude and frequency to extracellularly recorded multi-unit neural activity can wirelessly be transmitted and reconstructed with a good signal-to-noise ratio.

*Research Supported by NIH/NINDS 5RO1NS072385 grant to Sahin.
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II. METHODS

A 1 kHz sinusoidal signal was applied to the phosphate buffered saline (PBS) at room temperature through a pair of platinum (Pt) electrodes to simulate neural signals (Fig. 1). The amplitude of the induced voltage at the recording electrodes was 100μVpp. The prototype for the recording unit was built using discrete components. Pseudo neural signals detected through the Pt recording electrodes were first amplified by a two-stage FET/MOSFET (J201 and BS170) amplifier with a gain of 36dB, and then applied to the gate of another BS170, which had a piezoelectric element at the drain (Fig. 2). The drain current going through the piezoelectric element was thus modulated by the amplified neural signals.

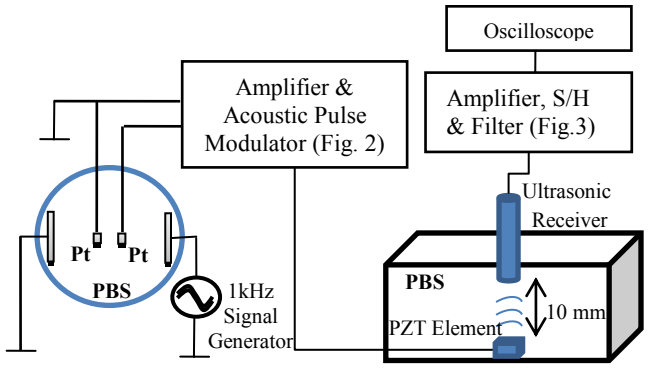

Fig. 1. The experimental setup for testing the acoustic transmission of pseudo neural signal.

A lead zirconate titanate (PZT) film with thin vacuum sputtered nickel electrodes on both sides (thickness 125µm, Piezo Systems, Inc. Woburn, MA) was used as a piezoelectric device to generate the acoustic signals. The PZT film was cut to a 2x2mm square size, which had a λ/4 thickness silver epoxy matching layer on the surface [5].

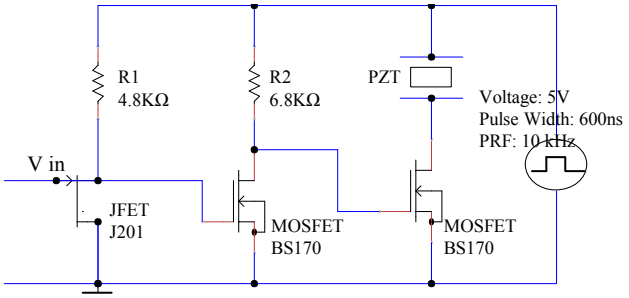

Fig. 2. The circuit diagram for the recording/modulating unit. The input terminals are connected to platinum electrodes. The circuit operates only during a 600ns voltage pulse applied as power.

The circuit was powered by a train of voltage pulses (each 600ns, 5V) from a signal generator at a rate of 10kHz. Thus, the circuit operated only during the ON cycles of the train at a duty cycle of 0.6%. This pulse duration was chosen as the optimum value to maximize the ringing of the PZT element in the transverse mode. The design of the power circuit will be the subject of a future study and thus not included here. The current/energy injected into the PZT element was modulated by the gate voltage of the MOSFET, which was the amplified version of the instantaneous value of the neural signal during the ON cycles of the pulse train.

The total circuit current that is withdrawn from the 5V supply is 4.61mA, which is the sum of 0.73mA by J201, 0.55mA by BS170, and 3.33mA by the second BS170. The total instantaneous power consumption of the recording/ modulating unit is therefore 23.05mW. Because the circuit operates at a duty cycle of 0.6%, the average total power is only 138µW. This value can further be reduced by lowering the pulse width, i.e. increasing the resonance frequency of the PZT element.

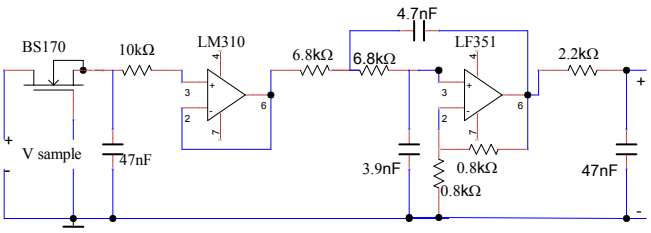

Fig. 3. The external circuit for extraction of the modulating neural signal from the acoustic signal. The signals detected by the ultrasound receiver is applied to the input after an amplification of 50dB (not shown). The circuit consist of a sample & hold (BS170 and LM310) followed by a low-pass filter at 5kHz. The signal shown on the bottom of Fig. 5 is applied to the S/H circuit here as a control (Vsample).

An ultrasonic receiver (focal length 10mm, Olympus NDT Inc., Waltham, MA) was placed 10mm above the PZT inside the PBS to wirelessly detect the acoustic signals. The external unit consisted of a 50dB high-frequency amplifier, a sample-and-hold circuit (S/H), and a low-pass filter at 5kHz to extract the modulated neural signal (Fig. 3). The S/H circuit samples the instantaneous value of the analog 'ringing' signal and holds the voltage for 100µs until the next sample. A 5 kHz low-pass filter smoothens the output waveform.

III. RESULTS

The pulse train observed at the output of the second amplification stage is shown in Fig. 4. Note that power voltage to the circuit has a pulsatile form resulting a similar waveform at each point in the circuit. Modulation of the pulse train amplitudes is better appreciated in the bottom plot with higher magnification. The modulation depth is about 6.25mVpp superimposed on a train of 1.25V pulses. The voltage modulation across the PZT is not very large (not shown) since it is mainly the current that is modified by the neural signal.

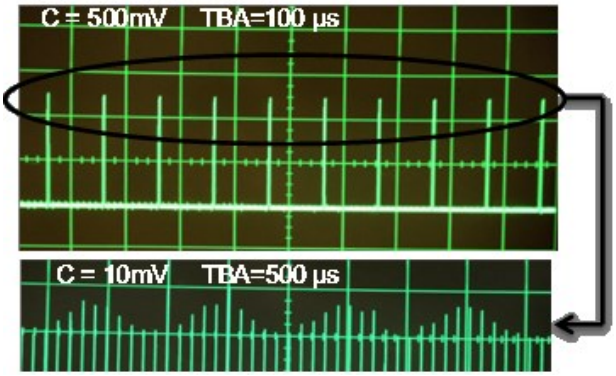

Fig. 4. The output of the second amplifier stage. Modulation of the pulse amplitudes can be observed in the magnified version of the plot on the bottom. The depth of modulation is 6.25mV for this input signal.

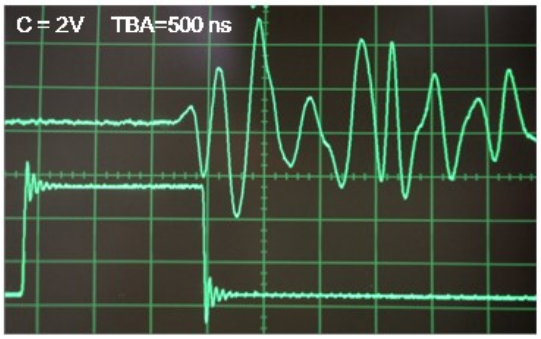

Fig. 5. The electrical ringing signal generated by the receiving transducer as a response to a single acoustic pulse. The control signal to the S/H circuit is shown on the bottom trace. The instantaneous value of the ringing signals is held at the falling edge of the control signal.

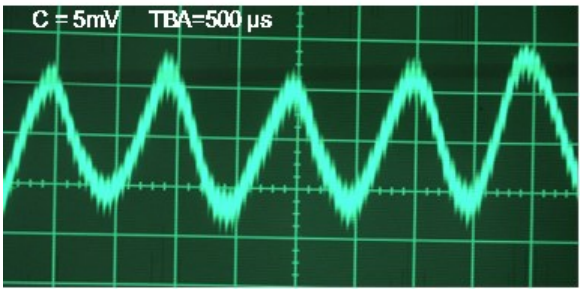

Fig. 6. The extracted sinusoidal waveform from the signal detected through the acoustic method. The original signal is a 100µVpp, 1 kHz sine wave at the recording electrodes. The SNR is 5.0.

Figure 5 shows the ringing waveform generated by the external ultrasonic receiver (before the S/H) as a response to a single acoustic pulse sent by the PZT. The S/H circuit is controlled by a voltage pulse that has the same rate (10kHz) and waveform with the power of the recording unit (bottom trace in Fig. 5). The extracted signal waveform after S/H and low pass filter is shown in Fig. 6. Signal-to-noise ratio was found to be 14dB (SNR=5).

IV. Discussion

The optimal width for the excitation pulse in order to maximize the mechanical output from a piezoelectric device is one half cycle of its resonance frequency [6]. The pulse width was set to 600ns in this study because the resonance frequency of the PZT element with the given sizes was measured to be around 800kHz. Considering that the ringing duration of the waveform observed at the ultrasound receiver output is about 5µs (Fig. 5), the pulse repetition rate can be as high as 200kHz. For a 1 kHz sinusoidal waveform, the 10kHz sampling rate was more than sufficient for a faithful reconstruction.

An important advantage of this recording technique is that the pulsed mode of operation will allow time multiplexing between multiple recording units and thus simultaneous neural recordings from multiple sites in the tissue. The pulse duration is a critical parameter in this design to increase the sampling frequency and the number of recording units. A smaller piezoelectric element will allow shorter pulse widths and consequently higher sampling rates as well as lower power consumption for each recording unit.

The two-stage neural amplifier can further be optimized for a higher gain and less power consumption. The power transfer paradigm into the recording unit was not discussed in this study. An efficient and wireless method of power transfer needs to be developed for the recording unit to be implantable. The future work will include minimization of device size through micro fabrication techniques to minimize the volume of tissue displaced by the implant.

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