A FULLY-PASSIVE WIRELESS MICROFABRICATED NEURO-RECORDER

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ABSTRACT

This paper reports a completely passive and wireless MEMS device for potential use in recording neuro-potentials *in-vivo*. Its operating principle utilizes an implantable circuit or “tag” to backscatter data to an external interrogator that supplies the fundamental carrier. The backscattering circuit relies solely on its nonlinear components, varactor diodes, which mix and backscatter neuro-potentials with the supplied carrier. Performance of the MEMS neuro-recorder was demonstrated using emulated and *in-vivo* neuro-potentials as low as 500 $\mu\text{V}_{\text{P-P}}$ and up to 3 kHz.

INTRODUCTION

Current wireless neuro-recording microsystems employ multi-component packages comprised of sophisticated circuitry located between the scalp and skull, which is then wired to micromachined electrode arrays implanted into the cortex of the brain [1-2]. In order to remove these interconnects and improve signal acquisition quality some have monolithically integrated the circuits onto the electrodes and/or fabricated die-level post-CMOS electrodes on-chip [3]. These advancements make it possible to monitor *in-vivo* potentials with extremely high spatial and temporal resolution. Nevertheless, challenges remain due to the complexity of wireless telemetry. To bypass some of this complexity, fully-passive techniques have been previously implemented in meso-scale systems [4-5]. In this paper, we present an alternative, significantly less complex microsystem for passive and wireless neuro-recording consisting of only two varactors, three MIM capacitors, and an on-chip planar antenna.

DEVICE OPERATION AND FABRICATION

Figure 1: A simplified schematic of the fully-passive and wireless neuro-recorder. $V_r(f_m)$ is the low frequency neuro-potential signal, f_0 is the carrier, and $2f_0 \pm f_m$ is the backscattered modulated signal.

The basic passive and wireless operation is illustrated in Fig. 1. An RF excitation carrier (f_0) generated by an external interrogator mixes neuro-potentials (f_m) through nonlinear varactors, backscattering third-order intermodulation products $2f_0 \pm f_m$. An illustration of the neuro-recorder is shown in Fig. 2a. The fabrication process uses seven masks (Fig. 2b). KOH-etched trenches on the front and back form the sockets for the varactors and probe feedthroughs, respectively. The frontside consists of a planar antenna, MIM capacitors, and varactors, and the backside is patterned with through-wafer interconnects to interface with neuro-potentials (Fig. 3).

Figure 2: a) An oblique view of the MEMS neuro-recorder with on-chip components and cross-sectional axis labeled (dashed line). b) Cross-sectional fabrication process flow: (a) patterning of Si/Si₃N₄/SiO₂ on front, (b) backside KOH etching for through-wafer interconnects and PECVD of SiO₂ for insulation, (c) depositing Cr/Au, and defining vias to electrodes on front, (d) depositing Cr/Au for bottom MIM plate and via interconnect, and PECVD of SiO₂ for MIM oxide layer, (e) depositing Cr/Au for antenna, MIM, and pads for diodes.

Figure 3: Photograph of a fabricated MEMS neuro-recorder placed above a dime (topside) with backside and close-up views.

TESTING

The MEMS neuro-recorder was characterized using i) emulated neuro-potentials and ii) *in-vivo* compound action potentials (CAPs) from a frog's sciatic nerve. A phase-synchronous demodulator was built to retrieve the wirelessly transmitted signals. The frog's nerve was stimulated by pulsing current into the lower end of the spinal column generating CAPs in the range of 10–1000 μ V down the nerve bundle. The CAPs acquired with the MEMS recorder ranged from 2–140 Hz and 500–1000 μ V.

RESULTS

The passive wireless telemetry operates at 2.2–2.45/4.4–4.9 GHz ($f_0/2f_0$) for emulated neuro-potentials up to 3 kHz (f_m) and as low as 500 μ V. Fig. 4 shows the measured frequency spectrum where a sinusoidal input signal generated by a function generator, of 3.4 mV at 400 Hz (f_m) is mixed with the backscattered carrier ($2f_0$, 4.41 GHz) resulting in the observed sidebands at 15 dB above the noise floor. Table 1 summarizes the measured specifications of the MEMS neuro-recording device. Fig. 5 shows CAPs from the frog as detected from the MEMS device and from measurements using the reference electrode.

Figure 4: Measured spectrum for 3.4 mV ($f_m = 400$ Hz) sinusoidal input and 14.8 dBm radiated from the source. Center backscattered frequency ($2f_0$) shown at 4.409999220 GHz with 400 Hz offset sidebands approximately 15 dB above the noise floor (boxed in).

Table 1: Summary of specifications for MEMS device.

Size		$12 \times 4 \times 0.5$ mm ³
Detected Input Signals	Bandwidth	5 – 3000 Hz
	Amplitude	≥ 500 μ V
	Distance	≤ 2.5 cm
RF Transmission	Radiated Power	0 – 18 dBm
	Frequency	2.2 – 2.45 GHz
RF Reception	Sideband Level	≤ -105 dBm
	Noise Floor	≈ -134 dBm
	Frequency	4.4 – 4.9 GHz

DISCUSSION

At this stage, the MEMS neuro-recorder may be suitable for detecting signals in the peripheral nervous system (PNS), especially in motor nerve bundles where CAPs reach up to hundreds of microvolts to several millivolts. The CAP measurements (Fig. 5) suggest the neuro-recorder may be capable of detecting neurological

signals as low as 500 μ V. Below 500 μ V, the current system becomes dominated by noise, including 60 Hz noise. The frequency of the noise may coincide with the frequency of the neuro-potentials and can completely screen out the targeted CAPs. However, because the current limitations in minimum detectable signal may result from external noise sources, future work to diminish noise may improve the device's sensitivity and enable signal detection on the same order as cortical potentials.

Figure 5: CAPs generated from a frog measured by a reference electrode (top, 0.1 V/div, 0.0025 s/div) at 500 μ V_{p-p} and wirelessly acquired from the MEMS neuro-recorder (bottom, 0.5 V/div, 0.0025 s/div). The sharp spikes represent artifacts of the pulsed current stimulation, which also travel down the nerve. The oscilloscope used 128 point averaging to remove some of the background noise.

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