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Research paper

Development of chip-less and wireless neural probe functioning stimulation and reading in a single device

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A B S T R A C T

A chip-less, wireless neural probe system was developed for stimulation of neurons and for reading of neural communications in the brain. The developed neural probe system is composed of a one-port surface acoustic wave (SAW) reflective delay line, neural firing-dependent ferroelectric capacitor, two antennas, and a network analyzer for reading of neural communications, as well as Schottky diode, static capacitor, and sharp metal tip for stimulation of neurons. The one-port SAW reflective delay line replaces existing wireless transceiver system composed of ~5000 electronic components and makes chip-less, wireless interrogation system possible. The probe for reading of neural signals employs PVDF ferroelectric capacitor which changes polarization and volume depending on neural firings. A 4.3 nH inductor was also connected between one-port SAW reflective delay line and reading probe to obtain a large linearity and high sensitivity through impedance matching effect. As electrical pulses imitating neural signals were applied to the reading probe at a 0.9% saline solution, amplitude changes in the reflection peaks were observed depending on the magnitude of applied electrical pulses. Good linearity and sensitivity were observed at the amplitude variations in terms of electrical pulses. The probe system for stimulation of neurons consists of Schottky diode, capacitor, and sharp metal probe. By modulating RF input power and the number of cycle from interrogator, stimulation amplitude and duration time of the resultant output pulses are manipulated. Coupling-of-mode (COM) modeling was also performed to predict device performances and to find optimal device parameters.

1. Introduction

There are ~10^{11} neurons in human's brain, and they interact with each other by releasing neurotransmitter and electrical pulses from the synapses at their terminals to function. Generally, the neurotransmitter released from a neuron cell is converted to electrical signal at the membranes of the cell bodies and dendrites at the other neurons, followed by passaging of the electrical signal to synapses to re-release. At the same time, charged sodium (Na^+) ions outside the neuron cell can influx into the inside via ion channels around cell membrane, as well as potassium (K^+) and chloride (Cl^-) ions inside the cell can flow out to the outside of the cell to sustain electrochemical concentration gradient. The electrical pulses at the inside of the neurons can reach to ~100 mV, while in case of extracellular neural signal measurement, a 10~100 μV electrical pulses are observed depending on the distance from the neural firing sources to neural probe. Normally, neuron generates 10–100 spikes per second during activity, but 1–10 spikes during resting. The frequency of the electrical pulses can be 100–300 Hz in case of low frequency neuron signals and 3–10 kHz for high frequency.

There have been a lot of efforts to develop neural probe system to read neuron's electrical pulses and to stimulate neurons in brain. These neural probes are largely categorized into two groups: (1) wired neural probes [1–4], (2) wireless neural probes [5–8]. In case of wired neural probes, presently existing silicon probes have been implanted into a paralyzed person and succeed a direct control of machine through only human thoughts. However, many issues are still left in the wired neural probes, which include a limited activity radius of a training animal due to the use of wired cables, a curling of cable line, a stress infliction to animals preventing righteous signal extraction, and biological contamination due to a manually handled chip. Wireless neural probe system resolves some issues from the wired neural probe such as a limited radius of a training animal and biological contamination emerging from manually handling of the chip, but there still remain many issues left including heavyweight of chips mounted on the surface of the cortex, signal distortions during passaging through wireless electronic circuits composed of thousands of transistors, and direct battery installation to activate the circuits and probes. Also, this wireless probe system is necessary two times signal processing: One signal process is performed at the first stage of wireless circuit and the other is carried out at the remote reader system. To solve these kinds of issues, we suggest a new wireless neural probe system comprising both reading and stimulation functions simultaneously in a single device. Fig. 1 shows

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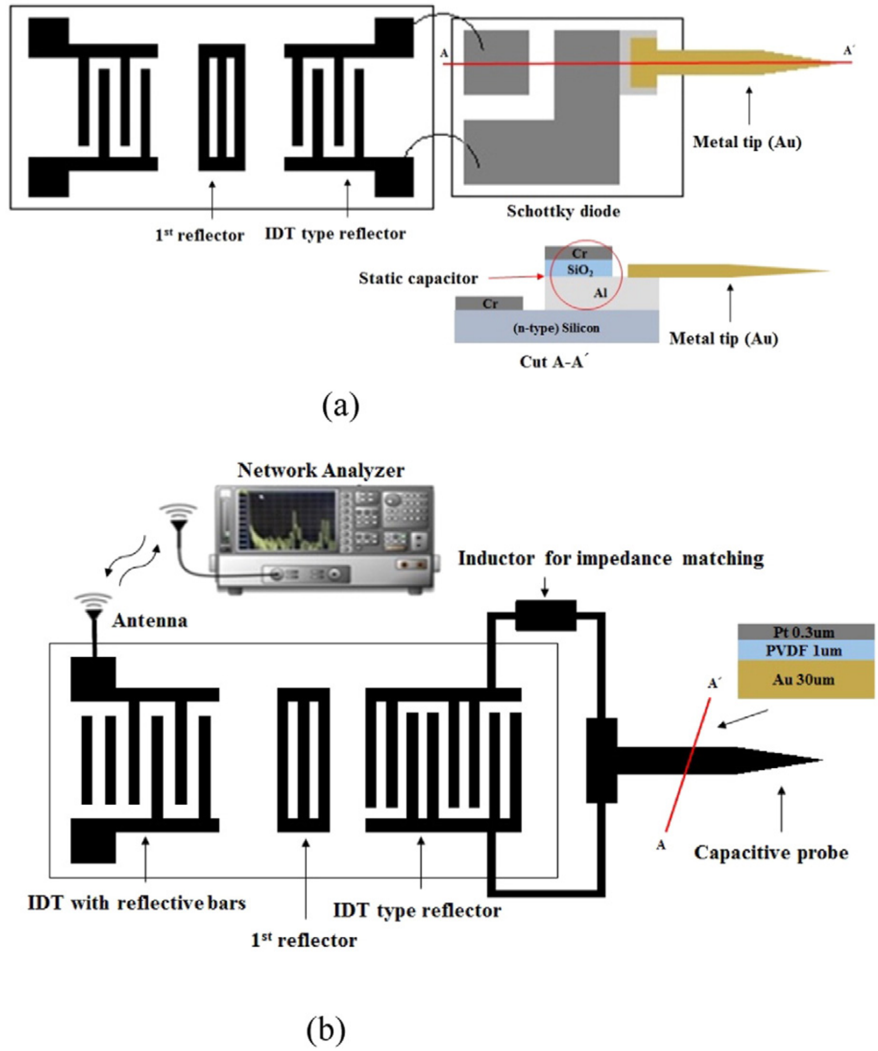

Fig. 1. Schematics of the developed (a) stimulation probe and (b) reading probe systems. Stimulation probe constitutes a one-port SAW reflective delay line, diode/capacitor/sharp metal probe to generate electrical pulses with different amplitudes and duration times, and two antennas for powering the system. In contrast, reading probe consists of a one-port SAW reflective delay line, a sharp ferroelectric capacitor, an inductor for impedance matching element, and two antennas.

schematic views of the developed wireless neural probe system. The system is composed of a one-port surface acoustic wave (SAW) reflective delay line for chipless wireless transceiver system, a sharp ferroelectric capacitor for reading probe, a inductor for impedance matching element, diode/capacitor/sharp metal probe for stimulation probe, and two antennas for powering the system. These systems have many advantages over presently reported wireless probes: it is wirelessly activated by antenna, so that it is battery-free. And it does not require any complicated transceiver systems (chip-less) and large power consumption from peripheral electronics circuitry, and it is small and light. This system also handles both reading and stimulation functions at the same time in a single device.

2. Operating principle

The operating principle of this system is as follows: As the interdigital transducers (IDTs) on the SAW reflective delay line receive electromagnetic (EM) energy from the network analyzer through an antenna, a shear-horizontal (SH) surface acoustic wave is generated on the 41° YX $LiNbO_3$ piezoelectric substrate and propagates toward the reflectors. The propagating SH wave is partially reflected by IDT type reflector, reconverted into EM waves by IDTs, and transmitted to the network analyzer via the antenna [9–12].

2.1. Stimulation probe

Fig. 1(a) shows the schematic for the developed probe for stimulation. A Schottky diode, static capacitor, and sharp metal tip were interconnected to generate neural stimulation pulses. When the SH surface acoustic wave reach to the 2nd reflector with split IDT type configuration, the mechanical wave is converted into AC electrical signals in which the peak-to-peak voltage can be reached to 100 μV depending on input EM power. The converted AC signals are an activation source of the Schottky diode and static capacitor. The Schottky diode rectifies only positive signals in AC to flow toward capacitor, and then the stored charges at the capacitor may move to metal probe during negative AC input signal. By modulating the input power and the numbers of AC cycles in EM energy, the resultant pulses are freely varied, providing desired electrical stimulation pulses.

2.2. Reading probe

Fig. 1(b) shows schematic of the developed probe for readings. It composes of one port SAW delay line, ferroelectric capacitor, and an inductor. The PVDF was sandwiched by two metals in which 30 μm-thick backbone gold was used for stiffness improver to provide sufficient mechanical stiffness during surgical insertion without buckling. The Pt was