Wireless Brain Implant for Dopamine Monitoring

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***Abstract*—Motoric symptoms in Parkinson's disease (PD) patients are caused by low level of dopamine (DA) concentration in the brain. Facilitating daily real-time and portable DA monitoring can improve the life quality of the patients. Miniaturized wireless brain implant can accommodate this purpose. The realization of this device requires compatible design on DA sensor, signal processing, and the wireless technology. For the sensor, the electrochemical method, Fast Scan Cyclic Voltammetry (FSCV), enables the sub-millisecond DA concentration measurement. Coupling this sensing method with RF technology and wireless power transfer can increase the device miniaturization and implantability. From our numerical analysis, the FSCV electrode with planar area approximately one square centimeter can accommodate the low-level DA concentration detection.**

I. Introduction

Nearly one million people in the US have Parkinson's disease (PD) with an annual total cost of approximately fifty two billion dollars. The progression of PD can be observed via motoric symptoms caused by the abnormal DA level in the brain. To ease the symptoms, a medication such as levodopa, is needed to normalize the DA brain concentration. Currently, the dosage is prescribed by medical personnel based on both approximation and "trial-and-error" methods. It even consumes longer time and high cost for laboratory analysis for precise measurement of DA level. In this paper, we propose a design of a nanostructure-based sensor for wireless detection of dopamine (DA) levels in brain tissue, specifically in the striatum.

The implant comprises three major elements, i.e. sensing electrodes, signal/data processor, and wireless communication part. Sensing electrodes should possess excellent chemical and electrical properties in order to exhibit sufficient detection sensitivity. A carbon-based electrode such as multilayer graphene (MLG) is a suitable candidate for this. A signal processor can be implemented using System on Chip (SoC) technology. The wireless communication part provides far-field wireless power transfer and wireless data communication to implement a biomedical telemetry system. To build up this wireless link, a miniature implantable antenna is an indispensable element and a radio frequency (RF) energy harvesting circuit needs to power up the sensing electrodes. Fig. 1 illustrates the proposed implementation of the wireless implant.

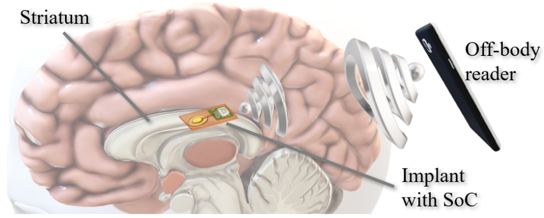

Fig. 1: System model.

II. Wireless Implant Design

A. Detection Method

Voltammetry is an electroanalytical method to obtain information of certain analyte by varying the applied potential (Volts) difference and measuring the current (Amperes). This technique is based on the reduction oxidation (redox) reaction of an analyte by the electrodes. In case of dopamine, dopamine-o-quinone (DoQ) is the oxidised product of dopamine during the voltage ramp-up applied to the electrodes and then DoQ can be reduced back to dopamine when the applied voltage ramps down. Therefore, this technique can be applied for dopamine sensing.

B. Sensing Electrode

Three electrodes are usually used for voltammetry technique. However, when in-vivo detection is targeted which means that smaller electrodes are utilised, two-electrode mechanism is used. In this case, auxiliary electrode can be excluded because the carbon material that is used in in-vivo detection is so small that it generates so low current (nA) that the Ohmic drop is negligible [1]. For the sensor design, the planar structure is desired especially for miniaturization purpose and considering the implant positioning in the brain [2]. The sensor material will be directly fabricated/transferred on/onto a Si-wafer. The required electrode area can be calculated using the Randles-Sevcik equation (1). With this formula, the ratio between the peak current (i_p) and electrode area (A) can be numerically simulated using MATLAB as a function of DA parameters (concentration, C_0, and diffusion coefficient, D_0).

$$\frac{i_p}{A} = 0.4463C\sqrt{Dv\frac{n^3F^3}{RT}}. \quad (1)$$

The simulation result depicted in Fig. 2 shows that for the low DA concentration in the brain (starting from a few

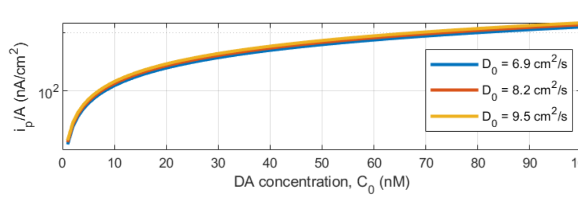

Fig. 2: Planar sensing electrode design.

TABLE I: Simulation Parameters.

Parameter	Value [Unit]	Description
F	96485.339 [C/mol]	Faraday's constant
R	8.31447 [J/K·mol]	Universal gas constant
T	310.15 [K]	Brain tissue temperature
n	2	No. of electrons in redox
D_0	(8.2±1.3E-7) [cm^2/s]	DA diffusion coeff. [3]
C_0	[1-100]x10^{-12} [mol/cm^3]	DA molar concentration
v	400 [V/s]	FSCV Scan rate

nM), the electrode area in the scale of square centimeters can induce a few nano amperes faradaic current. The simulation parameters are listed in Table I. The 1-100 nM DA concentration is sufficiently low to simulate the Parkinson's disease condition, considering the DA level in both normal tonic and phasic activities. The result represents the planar electrode area excluding the surface roughness of the electrode.

C. Wireless Power Transmission and Communication

To establish a real-time bio-telemetry communication continuously between the implant and an exterior monitoring unit, we need to deal with different challenges. The first challenge relates to designing an efficient and miniature antenna. The second challenge lies in the design of an optimized RF energy harvester that integrates with the antenna to provide sufficient voltage and offer high power efficiency for energizing the sensing electrodes. To meet the first challenge, we proposed a compact triple-band planar-inverted-F antenna (PIFA) with a volume of $11\times 20.5\times 1.8\text{mm}^3$, as shown in Fig. 3 (a), which fulfills all requirements of a bio-telemetry communication link [4]. The developed PIFA is intended for data telemetry at the Medical Device Radiocommunication Service (MedRadio) band (402 MHz), while the power transfer operation and switching between sleep/wake-up modes are assigned at the Industrial, Scientific, and Medical (ISM) bands of 902 and 2400 MHz, respectively. The prototyped model employs a 50Ω coaxial cable via an embedded 0.6 mm radius pin into the radiator to feed the PIFA and a shorting-strip connects the radiating patch to the ground plane in the y-z coordinate plane vertically. In the initial stage, the dimension of the PIFA was computed to operate at 902 MHz applying the equation of $f = C_0/\left(4\sqrt{\varepsilon_r}(L + W + h + W_{Shorting-strip})\right)$ [4], where C_0 is the light speed in free space, ε_r depicts the substrate relative permittivity, L and W are the antenna's length and width, respectively, h denotes the substrate thickness and $W_{Shorting-strip}$ defines the shorting strip width. According to the formula, we were able to shrink the antenna size utilizing the high-permittivity substrate/superstrate (Rogers RO3210; ε_r=10.2, $tan\delta$=0.003, h = 0.635 mm) and isolate the PIFA from surrounding lossy human tissues by covering the radiating elements with superstrate. In addition, we encapsulated the PIFA with silicone (MED-2000, Avantor Inc., U.S.; ε_r= 2.2, $tan\delta$= 0.007) to be biocompatible with the surrounding tissues. After that, we downsized the antenna by inserting cutting slots into the radiating patch and then created MedRadio resonance by meandering these slots and making the current path longer. Finally, we added one more slot close to the feeding point for

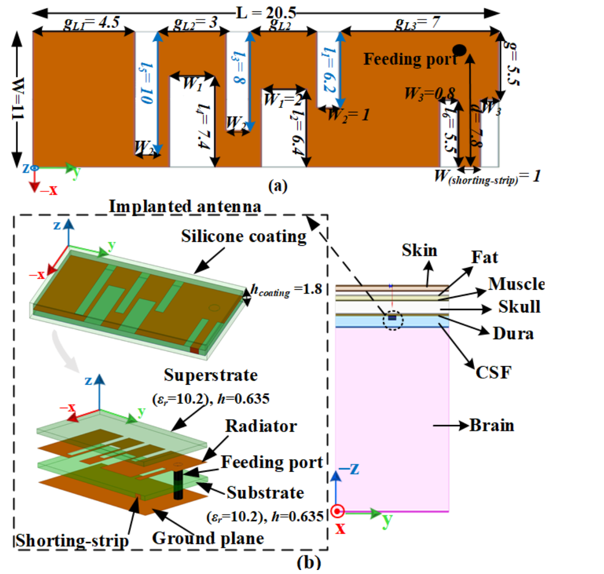

Fig. 3: (a) The proposed triple-band meandered PIFA geometry, (b) The numerical 7-layer human head model with implanted PIFA (all dimensions are in the units of millimeters) [4].

exciting the antenna to operate at 2400 MHz. We simulated and analyzed the developed PIFA using a 7-layer head model, as illustrated in Fig. 3 (b), where the antenna implanted in the cerebrospinal fluid (CSF) layer in the cranial cavity at 13.25 mm depth. Afterward, we tested the prototyped antenna in head SAR liquid, where we attained proper radiation characteristics of the PIFA to propagate outwards from the head.

To accomplish our scenario, we need to optimize a power management unit employing an RF energy harvester to match properly with the developed PIFA and ensure to deliver the maximum available RF power at 902 MHz for powering up the sensing electrodes placed in the striatum. Taking the real application approach into account, it is required to introduce a developed data managing circuit for transmitting the DA concentration level to an exterior monitoring unit at 402 MHz operating frequency of PIFA. It is worth noting that the third resonance (2400 MHz) of PIFA has been reserved for switching between the wake-up and sleep modes using RFID tag IC to conserve the implant's power energy and enhance the implant lifetime.

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