Modeling of an optrode microdevice for infrared neural stimulation

PhD thesis

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Prelude of research

The effect of the infrared neural stimulation is due to the temperature changes of the intracellular water. Water has absorption peak in near-infrared range at 1500 nm and 1900 nm, therefore most of the excitation energy will absorbed and turned into heat [1].

Infrared neural stimulation decreases the dementia caused by Alzheimer and Parkinson [2]. For the treatment of Alzheimer-diseases the infrared light sources have to be laid on the surface of the skull, because the radiation could penetrate 8-10 mm deep into the cortex. In case of Parkinson the brainstem has to be stimulated, with the help of an optical fiber inserted into the brain [3].

Infrared neural stimulation is the research topic of Zoltán Fekete and his research team – PPKE ITK Implantable Microsystems Research Team–, whose work I have joined. The silicon microdevices fabricated by the team are biocompatible and provide the ability for electrical and thermal measurements of the brain during the stimulation [4].

Goals

The aim of my PhD thesis is the investigation of an optrode microdevice for infrared neural stimulation, which has one of the key roles in the medical-biological research of the central nervous system. The goal of the medical research is to change the arise and propagation of the action potential by infrared light, which provide us treatment for neurodegenerative diseases. The temporal and spatial behavior and the values of the temperature-change are key parameters, therefore knowing their precise values are very important for the set of the biological experiment.

My goal was to develop a physical model, which could anticipate the temporal and spatial temperature distribution in the brain, using the physical properties of the excitation light and the optrode, and is able to plan of the biological experiment and the optimization of the device. Using the numerical model I will investigate the propagation, the in and out coupling and the surface scattering and the absorption of the excitation light. Using the heat transfer equation with the absorbed optical intensity as heat source term I will calculate the spatial and temporal temperature distribution of the excited brain.

The mechanical and optical properties of the optrode will be optimized to achieve the best out-coupling efficiency value. The validation of the model happens with the help of the optical and thermal measurements.

New scientific results

I. I am the first who developed the complex optical model of a Michigan-type silicon optrode. Using the validated optical model I showed that the surface light scattering has an important effect on the efficiency of the device. The 46% out-coupling efficiency calculated in case of ideally smooth surface decreases to 32±2% value taking into account the surface scattering. [S1, S2, S5]

II. I developed the finite element thermal model of the biostimulation. Modeling a water-heating experiment I determined the spatial and temporal temperature distribution of the medium, which showed well agreement with the measured values. I found out that a typical medical excitation causes 3 °C maximal temperature rise, 0,1-0,2 mm distance from the optrode tip. [S2, S6]

III. I implemented the coupled optical and thermal model with the mechanical model of the device. Using the complex mechanical-optical-thermal model I optimized the optrode geometry according the mechanical stability, optical efficiency and the maximal temperature rise of the medium. I found out that eliminating the in-coupling lens and elongated the fiber guide length with 0,94 mm leads to 40,1% optical efficiency, with the same mechanical strength. I investigated the effect of the tip shape and showed, that using 15° degree tip angle instead of the original leads to 45,2% efficiency and 4,42°C maximum temperature rise, beside the same excitation parameters. [S3, S7]

IV. Using the thermal model of the infrared brain stimulation I found out, that the model gives 5% higher peak temperature values than the water approximation, and shows less anisotropic temperature distribution. Using the model to simulate an animal experiment the simulated temperature rise showed very good agreement with the measured values. I found out that the temperature rise is well localized in space and could be controlled by the input excitation power.

References

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