Analysis of Nonresonant Powering of Magnetoelectric Nanoparticles for Deep Brain Stimulation in Mice

Prachi Kumari, Arianna M. Fossati, Pavithra Gopinath, Avishek Sarbajna, and Kristen L. Kozielski, *Member, IEEE*

***Abstract*— Wireless, remotely powered, and small-scale devices provide promise for less invasive neuromodulation. Remote powering often relies on resonant carrier frequencies, which make powering efficiency and depth negatively correlate with device size. Powering of magnetoelectric (ME) nanoparticles has been demonstrated in the mouse deep brain using nonresonant magnetic signals, but the powering mechanism has not yet been evaluated. Herein, we analyzed remote powering of ME nanoparticles via a nonresonant magnetic field in the mouse deep brain.**

I. Introduction

Remote powering of neural devices using inductive coils, antennas, or acoustic powering of piezoelectrics often relies on resonant carrier frequencies to optimize power transfer. However, this leads to a tradeoff in signaling depth and device size, making deep brain modulation impossible. In previous work [1], we experimentally demonstrated wireless deep brain stimulation in mice using a nonresonant, magnetic carrier signal and ME nanoparticles, which transduce magnetic signals into an electric field. Herein, we computationally analyzed remote powering of ME nanoparticles for neural stimulation in the deep brain of mice. We examined transmission of the carrier magnetic signal through the brain, ME signal transduction, and the local electric field generated in the tissue. This model can be expanded in the future to analyze the potential of ME materials as wireless neural devices.

II. Methods

A volume of ME nanoparticles was modeled as a 0.0088 ± 0.0023 mm^3 sphere located bilaterally within a model of the mouse subthalamic region, to match previous experimental conditions (Fig. 1A) [1]. The SIM4LIFE Quasi-Static Electromagnetic Solver (EM-QS) was used to model a 220 mT DC magnetic field, and a 6 mT, 140 Hz AC field through a 9 mm sphere with dielectric properties matching bone (thickness = 0.300 mm) and brain tissue. The magneto-mechanical-electro coupling phenomenon of a single nanoparticle (30 nm radius $CoFe_2O_4$ (CFO), 10 nm $BaTiO_3$ (BTO) shell) was computed using finite element analysis (COMSOL Multiphysics). Input values for CFO saturation magnetization (23.5 kA/m) and magnetic susceptibility (198) were measured using a MicroMag Alternating Gradient Magnetometer, using a CFO nanopowder (Sigma). The von Mises stress due to magneto-mechanical coupling in CFO was applied as a boundary load to the BTO shell, and stress-charge coupling was used to calculate a voltage. The SIM4LIFE EM-QS Ohmic Solver was used to calculate an electric field in tissue surrounding the nanoparticles, and a radius of activation was determined using 120 V/m as a deep brain activation threshold [2].

III. Results

The magnetic field strength through the mouse brain tissue was 175 kA/m DC, and 4.77 kA/m AC along the axis of nanoparticle administration with no phase shift. von Mises stress on the surface of CFO was calculated to be 1.4 x 10^{-2} N/m^2, yielding a voltage of 1.34 x 10^{10} V/m^3 on the surface of the BTO shell. The radius of activation was 359 ± 64 μm, which correlated well with our experimental results (203 ± 129 μm, as measured by cFos staining) [1].

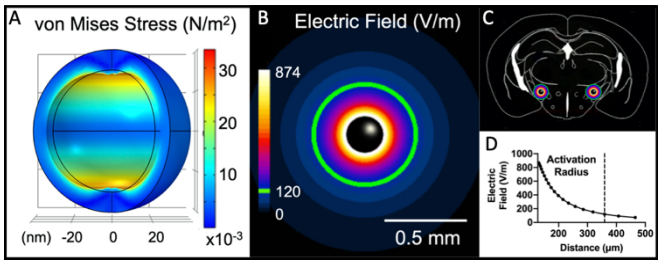

Figure 1. von Mises stress applied to the BTO layer (A). Plot showing the electric field around the volume of nanoparticles, with the radius of activation in green, zoomed (B), and scaled to coronal section AP: -2.06 (C). Plot showing the electric field versus distance from the particle center (D).

IV. Conclusion

The work herein shows for the first time the theoretical feasibility of remote powering of ME nanoparticles using a nonresonant magnetic carrier signal. The results also support earlier experimental findings with regard to the spatial selectivity of ME neurostimulation. Future work to optimize ME neural devices will require evaluation of other ME material sizes and geometries, analysis of depth and carrier frequency limits, and examination of stimulation in human anatomical brain models.

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P. Kumari, A.M. Fossati, P. Gopinath, A. Sarbajna, and K.L. Kozielski are with the Department of Bioengineering and Biosystems, Institute of Functional Interfaces, Karlsruhe Institute of Technology, Karlsruhe, 76344 Germany (e-mail: prachi.kumari@kit.edu; ariannamaria.fossati@mail.polimi.it; pavithra.gopinath@kit.edu; avishek.sarbajna @student.kit.edu; *Correspondance to:* k.koz@kit.edu, +49 721 608-23588).

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