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Enhancing Coil Design for Micromagnetic Brain Stimulation

Giorgio Bonmassar¹, Laleh Golestanirad¹, and Jiangdong Deng²

¹A. A. Martinos Center, Harvard Medical School, Massachusetts General Hospital, Charlestown, 02129 MA, USA

²Center for Nanoscale Systems., Harvard University. Cambridge, 02138 MA, USA

Abstract

This work further advances the micromagnetic stimulation (μ MS) technology, which has shown the capability of stimulating the nervous system using magnetic induction in a focal region of tissue by discharging a time-varying current through a sub-millimeter size coil. However, μ MS was originally based on commercial off the shelf (COTS) inductors, which are designed to maximize efficiency and minimize its losses albeit shielding off the magnetic field from reaching the neural tissue. In this work, we study and fabricate microscale coil structures for next-generation μ MS devices. The coil was designed to optimize the flux injected into the tissue by using a planar square spiral coil geometry, which was previously shown to be optimal for neuronal stimulation. The results of the electromagnetic Finite Elements Method (FEM) simulations of the proposed μ MS device show that even though the spiral has a fully symmetric design, it nonetheless exhibits an asymmetry in the induced electric field in the tissue that can potentially be used for activating neurons with a specific axonal orientation. Such devices could become the brain and heart stimulators of the future with their contactless ability to deliver the neuronal stimulation needed for therapeutic efficacy in patients in need of implantable cardioverter-defibrillators or pace-makers, or patients with Parkinson's disease, epilepsy.

Introduction

Micromagnetic stimulation (μ MS) near excitable tissue induces a localized current gradient in both time and space adequate to activate neurons, as demonstrated *in vitro* by activating retinal ganglion cells [1]. We have also shown that μ MS is capable of activating neuronal circuitry in-vivo in rodent models, using acutely implanted micro coils to activate neurons of the inferior colliculus [2]. These experiments have shown that μ MS has the promise of introducing new paradigms in the stimulation of the human nervous system. Although electrical manipulation of neurons continues to evolve using novel electrode designs [3], μ MS has several advantages over the traditional electrical stimulation: (1) it does not require charge-balanced stimulation waveforms, (2) it can activate neurons with specific axonal orientations, (3) it has improved biocompatibility when coated with implantable grade polymers, and (4) it is a potentially magnetic resonance imaging (MRI) compatible technology. The *in-vitro* studies [1] showed that μ MS coils placed parallel to the surface of the tissue can activate neurons differentially based on coil orientation. Furthermore, previous electromagnetic simulations indicate that single-layer planar spiral geometries are more efficient in eliciting neural activation because they induce significantly higher electric fields

(up to 5 folds) into the tissue compared to solenoidal or helical coils [4]. The quandary is that μ MS technology, which was first developed in our laboratory [1, 2], was entirely based on commercial components off the shelf (COTS), which are readily available to researchers. However, COTS inductors are designed to maximize efficiency (Q-factor), which consists of trapping the generated magnetic field to minimize its losses. Unfortunately, this type of design reduces the magnetic flux into the tissue and thus greatly reduces the stimulation efficacy. Instead, the magnetic flux of single-layer planar spiral coils may directly expose the tissue without trapping the magnetic flux. In this work, we studied and fabricated preliminary prototypes of a square design version of micro-scale single-layer planar spiral coil structures as μ MS devices. Furthermore, we studied electric field \mathbf{E} distribution over space with numerical electromagnetic simulations. The neural activation function is proportional to the derivative of the \mathbf{E} along the axon's axis. The Neurons which oriented perpendicular to the long axis of the solenoid are more likely to be activated as they experience higher \mathbf{E} .

Simulations

The finite element method (FEM) was used to study the electric field induced by a microscopic planar square spiral coil of $300\mu\text{m}\times 300\mu\text{m}\times 100\mu\text{m}$. This design was the stencil wafer that we have constructed to ultimately manufacture the coil (see below). Magnetically induced eddy currents in the tissue were calculated by solving the equation below [5]:

$$\nabla \times 1/\mu(\nabla \times \mathbf{A}) = (\sigma + j\omega\epsilon)(-j\omega\mathbf{A} - \Delta \phi)$$

Where \mathbf{A} , ϕ , α , ϵ and ω represent magnetic vector potential, electric scalar potential, permeability, permittivity, and the angular frequency, respectively. ANSYS Maxwell (ANSYS Canonsburg, PA, USA) was used to solve the T- Ω formulation of the Maxwell's equations as conventionally performed in the study of transcranial magnetic stimulation [6, 7]. Electric field strength induced by the a μ MS coil placed $50\mu\text{m}$ above the surface of the tissue ($\sigma = 0.47 \text{ S/m}$) was calculated when the coil was fed excited with a 70 kHz sinusoidal current [1]. The geometric model consisting of the coil connected to a current source on top of a $1.6\text{mm}\times 1.6\text{mm}\times 400\mu\text{m}$ slab of tissue. The current in each turn was the same for all the simulations was set to the value of $I_r = 1 \text{ A}$.

Materials and methods

Fig. 1 illustrates a CAD drawing of the proposed single layer planar square spiral coil of dimensions $300\mu\text{m}\times 300\mu\text{m}\times 100\mu\text{m}$ which will be made from copper based on a $10\mu\text{m}$ trace width design. The two side structures around the spiral are simple pads that retain the $10\mu\text{m}$ trace width structure for uniformity, the lower pad will be connected to the center of the coil with a microwire. In Fig. 2 is shown Scanning Electron Microscope (SEM) images (Hitachi SU-8230) of a $100\mu\text{m}$ thin 100mm Si wafer (undoped, orientation $\langle 100 \rangle$ and $> 5 \text{ k}\Omega\text{-cm}$ resistance). The SEM images were acquired after photolithography, and deep reactive ion etching (DRIE) performed at the Center for Nanoscale Systems at Harvard University. Photolithography was performed as follows: a $7\mu\text{m}$ thick layer of SPR 220-7 was spin coated on the thin wafer after hexamethyldisilazane (HMDS) deposition. This priming step

was crucial for adhesion promotion, and the thin wafer was dehydrated through a series of heated (150°C) evacuation and dry nitrogen refills, followed by HMDS vapor inserted into the evacuated chamber forming a monolayer. The coated wafer was then exposed to a laser direct writing system (uPG501, Heidelberg Instruments Inc, Heidelberg, Germany) with a pattern shown in Fig. 1, and developed using AZ 400K for 4 minutes, without stirring. The wafer was then etched with a deep reactive ion etching system (DRIE-Rapier, SPTS Technologies, Newport, UK), which etched the thin wafer using Bosch switched processing for obtaining the steep vertical profiles (Fig. 2). The stencil wafer is still part of work in progress and will then be used to grow copper inside it using copper electroplating deposition.

Simulation results

Fig. 3 shows the FEM results of the electric field induced in the tissue exhibits an asymmetry along the x-axis. This electromotive force estimated by the FEM simulations and induced by the magnetic flux of the coil (Fig. 4) has a component along mainly one axis, which could be exploited to activate axons with a specific orientation.

Conclusions

In this work, we studied using the Finite Elements Method (FEM) and fabricated microscale coil structures for next-generation μ MS devices. The coil was a planar square spiral coil geometry, which was previously shown to be optimal for neuronal stimulation. The results of the FEM simulations show that even though the single layer planar spiral has a fully symmetric design, it has nonetheless exhibited an asymmetry in the induced electric field magnitude in the tissue that can be exploited for activating neurons with a specific directionality, one of the salient characteristics of μ MS. This technology could become potentially the pacemaker and brain stimulator of the future given the μ MS contactless ability to deliver the neuronal stimulation, which is needed for therapeutic efficacy in patients with Parkinson's disease, epilepsy, in need of implantable cardioverter-defibrillators or pace-makers, etc.

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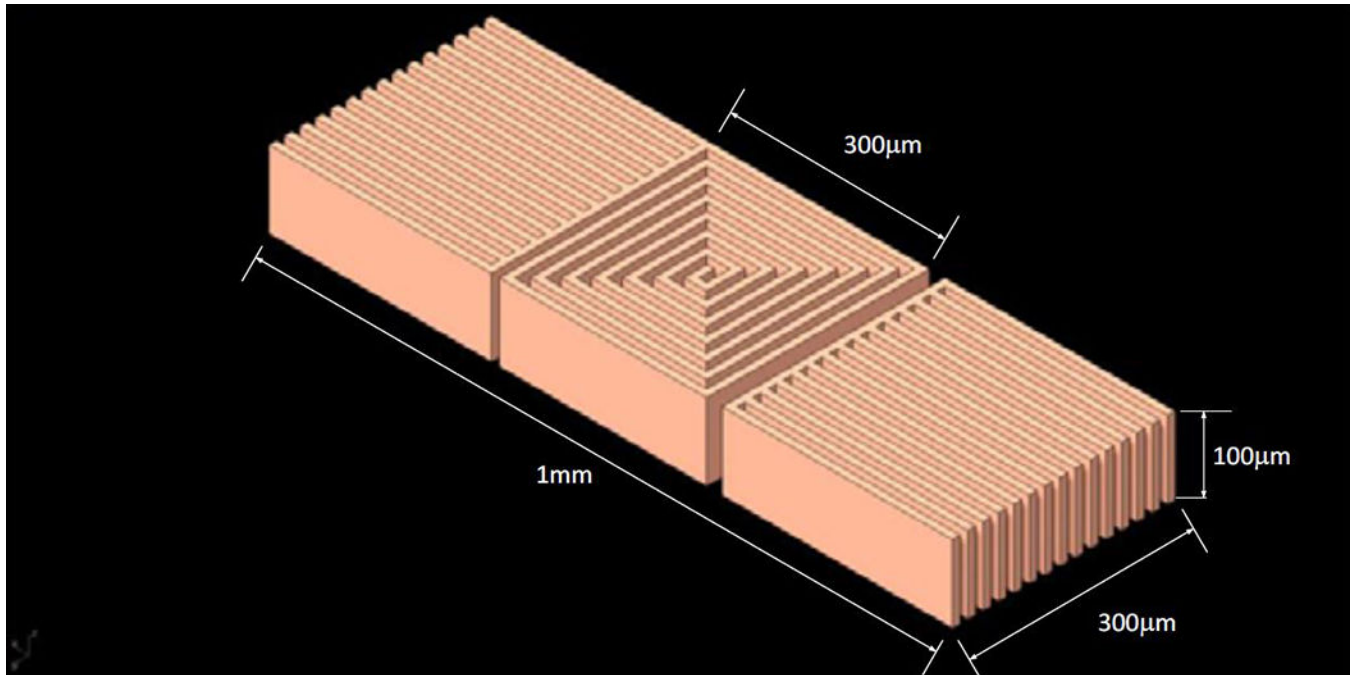


Figure 1:

The proposed single layer planar square spiral coil of dimensions which is in copper based on a 10µm trace width. The side structures are simple pads that retain the 10µm trace width structure for uniformity.

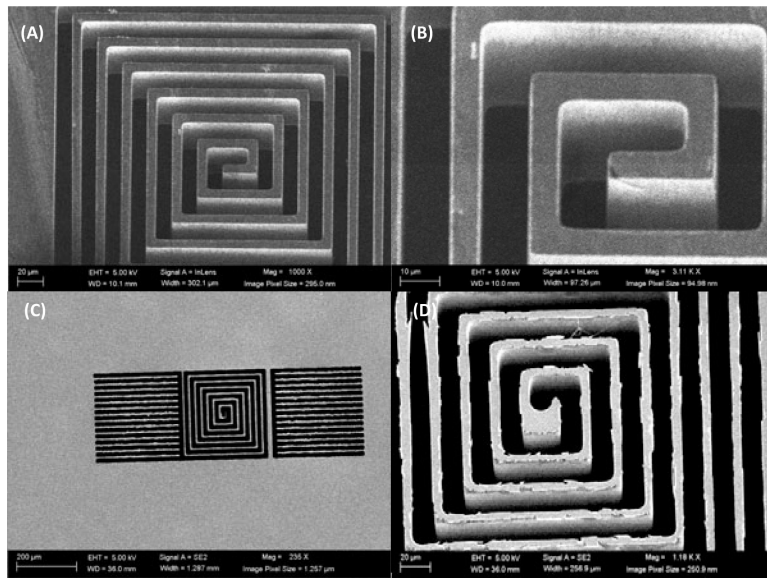


Figure 2: SEM images of the stencil wafer. Top view of the six turns single layer planar spiral coil (A), zoomed in view of the coil from the front (B), overview of the entire coil structure from the back side (C) after flipping the stencil wafer over showing that the DRIE reached through and through, and details of the back side of the stencil wafer that show a bottom footing (D).

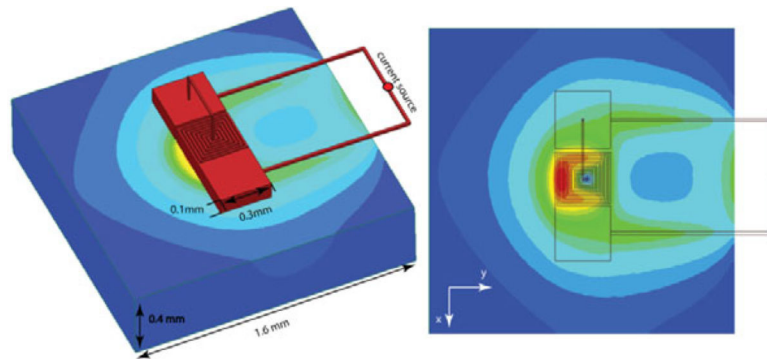


Figure 3:
The Finite Elements Method (FEM) Simulations. (Left) The geometric model consisting of the coil connected to a current source on top of a slab of tissue. (Right) The electric field induced in the tissue exhibits an asymmetry, which allows stimulating neurons along the direction of the x-axis.

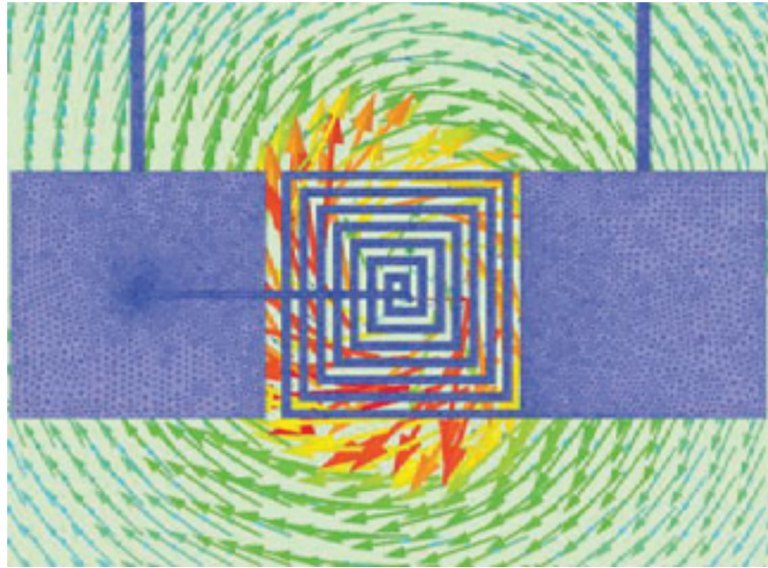


Figure 4:
The induced eddy currents in the tissue generated by the μ MS coil magnetic flux, which was estimated by the FEM simulations.