Planar Figure-8 Coils For Ultra-Focal And Directional Micromagnetic Brain Stimulation.

H. Jeong

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

J. Deng

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

G. Bonmassar

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

Abstract.

Recently, white matter fiber tract pathways carrying neural signals through the brain were shown to follow curved, orthogonal grids (1). This abstract focuses on how these 3D fiber grids may be stimulated using μMS, a new type of neuronal stimulation, which generates microscopic eddy currents capable of directionally activating neurons (2,3). One of the most remarkable properties of this novel type of stimulation is that the orientation of the applied μMS fields provides unique activation of neuronal elements not seen with traditional electrical stimulation. Developed initially to stimulate single neurons, μMS uses ultra-conductive micro-traces capable of carrying current pulses large enough to elicit neural activation through electromagnetic (EM) induction. In this regard, the μMS mechanism of action is similar to transcranial magnetic stimulation (TMS). However, where TMS can only generate broad and non-focal activation, μMS has an ultra-small dimension, inducing electric fields with a much higher spatial gradient, rendering it inherently more efficient to elicit focal neural activation.

Methods & Results.

The planar 2-D coil array manufacturing was performed at the Center for Nanoscale Systems (CNS) at Harvard University. Fig. 1 shows the optical and Scanning Electron Microscope (SEM) images (by Hitachi SU-8230) of planar 2-D coil arrays on a SU-8 substrate. Our simulations indicate that such 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 coils (please see (4)). This result follows from the fact that the maximum energy that can be stored in the magnetic field of an ideal inductor is:

$$\mathbf{W} = \frac{1}{2}\iiint \boldsymbol{J}(x,y,z)\cdot\boldsymbol{A}(x,y,z)\,dx\,dy\,dz = \frac{1}{2}Li^2 \tag{1}$$

where $\boldsymbol{A}$ is the magnetic potential, and the curl is the magnetic flux density (i.e., $\boldsymbol{B} = \boldsymbol{\nabla}\times\boldsymbol{A}$). In an actual inductor, the portion of the energy W that is lost is available for eliciting neuronal activity, even though this loss reduces the Q-factor or the efficiency and the inductance of the coil. Thus, to maximize the flux in the tissue, a low Q-factor is preferable in the planar coil, and the μMS has less than 0.5 Q-factor. Moreover, further EM numerical simulations showed that the actual E-fields induced by planar 2-D coils are indeed capable of higher focality by stimulating mostly large fibers with E-field thresholds of 2 V/m **(Fig. 2, 3**). The length of activation over the cylinder's volume representing the crossing fiber was calculated using the threshold of E-field estimated using voltages commonly used in our rat experiments.

Conclusions.

Numerical simulations provide a crucial insight into the mechanism(s) of micro-magnetic nerve stimulation and should be used both during the design process and to interpret the neural responses. Based on these results, the long solenoid design optimizes the Q-factor but renders the bulk of the magnetic energy inaccessible. An alternative is the use of multiple slimmer coils that maximizes neuronal tissue access to the magnetic flux produced by μMS coil to optimize neural stimulation. An initial prototype of the stencil was built using photolithography based on SU-8 technology, suggesting that the structure is manufacturable.

References.

(1) Wedeen VJ, et al. *The geometric structure of the brain fiber pathways*. Science. 2012.

(2) Bonmassar, G., et al., *Microscopic magnetic stimulation of neural tissue.* Nat Commun, 2012.

(3) Park, H.J., et al., *activation of the central nervous system induced by micro-magnetic stimulation.* Nat Commun, 2013.

(4) Bonmassar, G. et al.. Enhancing Coil Design for Micromagnetic Brain Stimulation, MRS Advances. 2018.

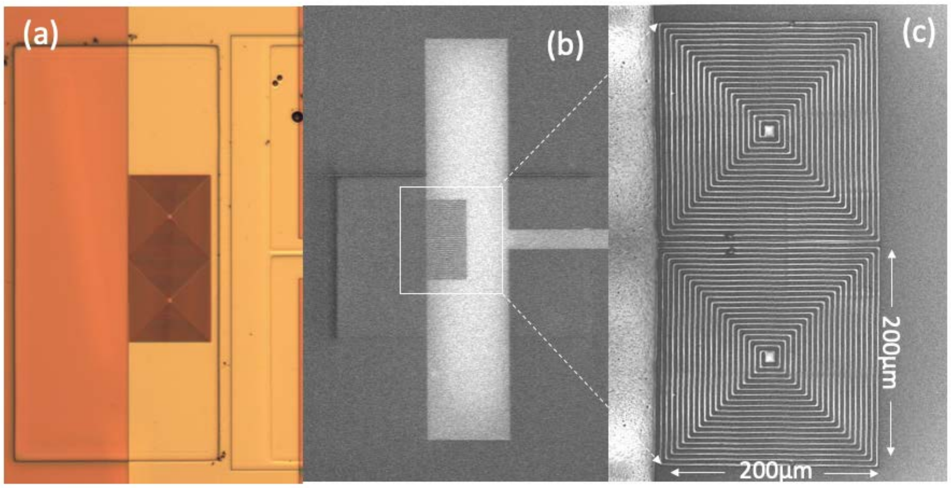

Fig. 1: ***The μMS figure-8 manufacturing at CNS.*** (a) *Optical microscope images in the right a 500nm layer of SPR-700 on top. (b) Top view of the thirteen turns Au traces of the proposed planar figure-of-eight coil using Scanning Electron Microscopy (SEM), (c) zoomed-in view of the coil on top of a SU-8 substrate and SEM images of the 200μm figure-8 coils.*

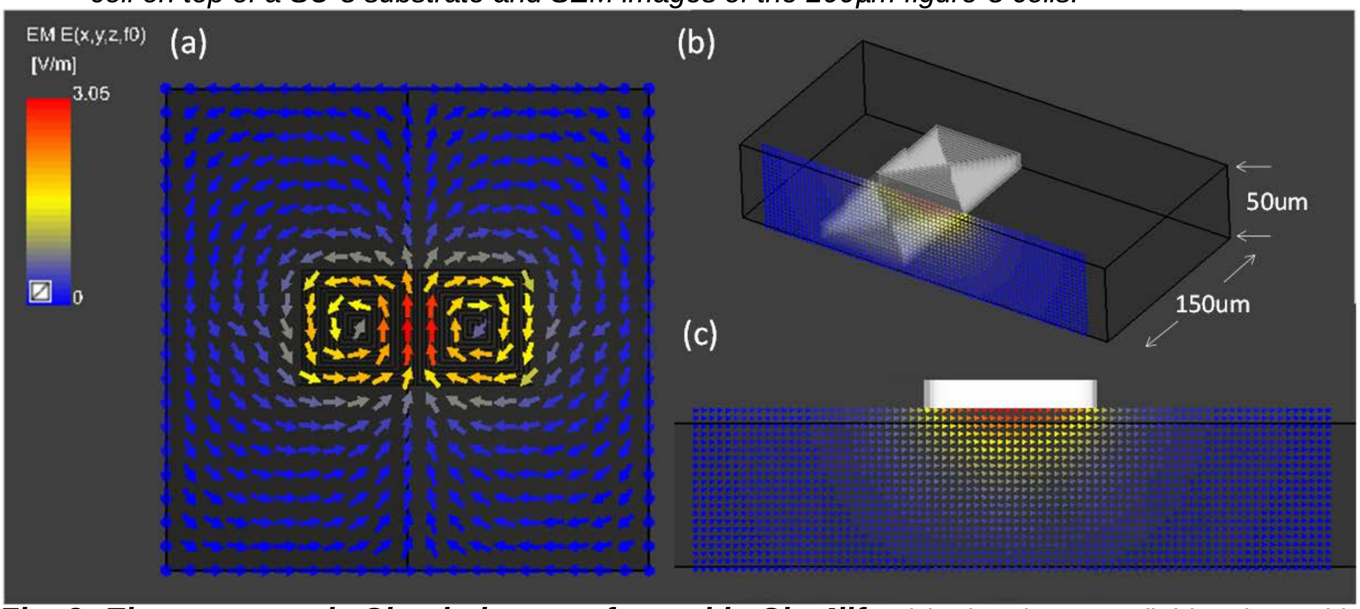

Fig. 2: Electromagnetic Simulations performed in Sim4life. *(a) Electric vector field estimated in the tissue underlying the coils. (b) simulations were performed in a container of physiological solution. (c) Cut section showing the E-field strength in between the two figure-8 coils.*

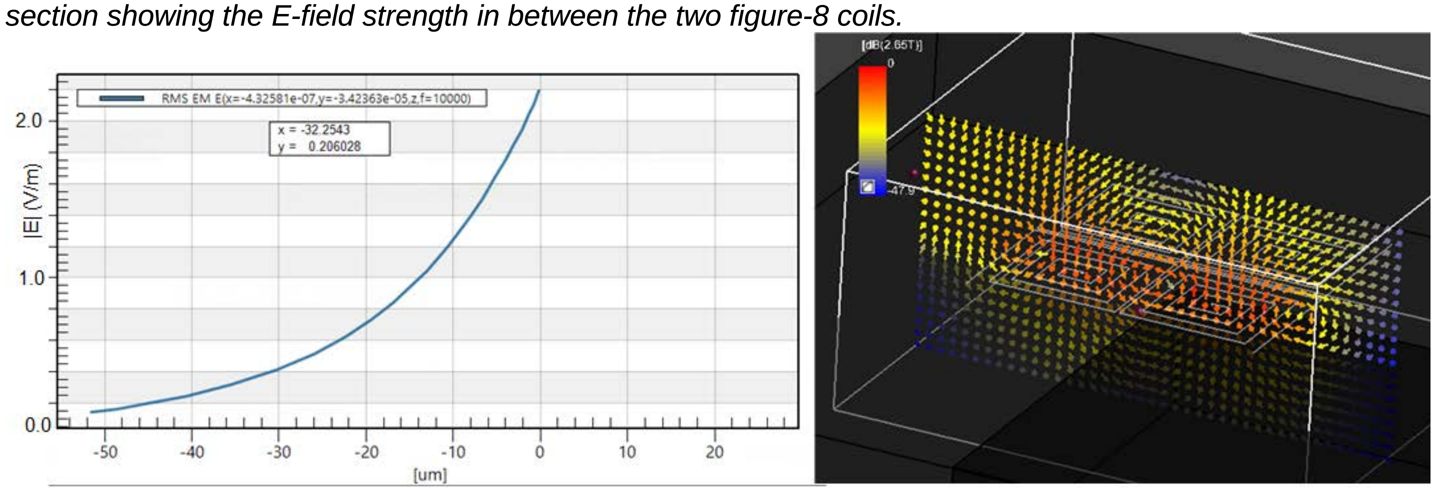

Fig. 3: EM simulations. *(Left) the magnitude of the electric field as it penetrates the tissue vertically and in the middle axis. (right) magnetic field vector.*