Magnetic neural control with nanoparticles

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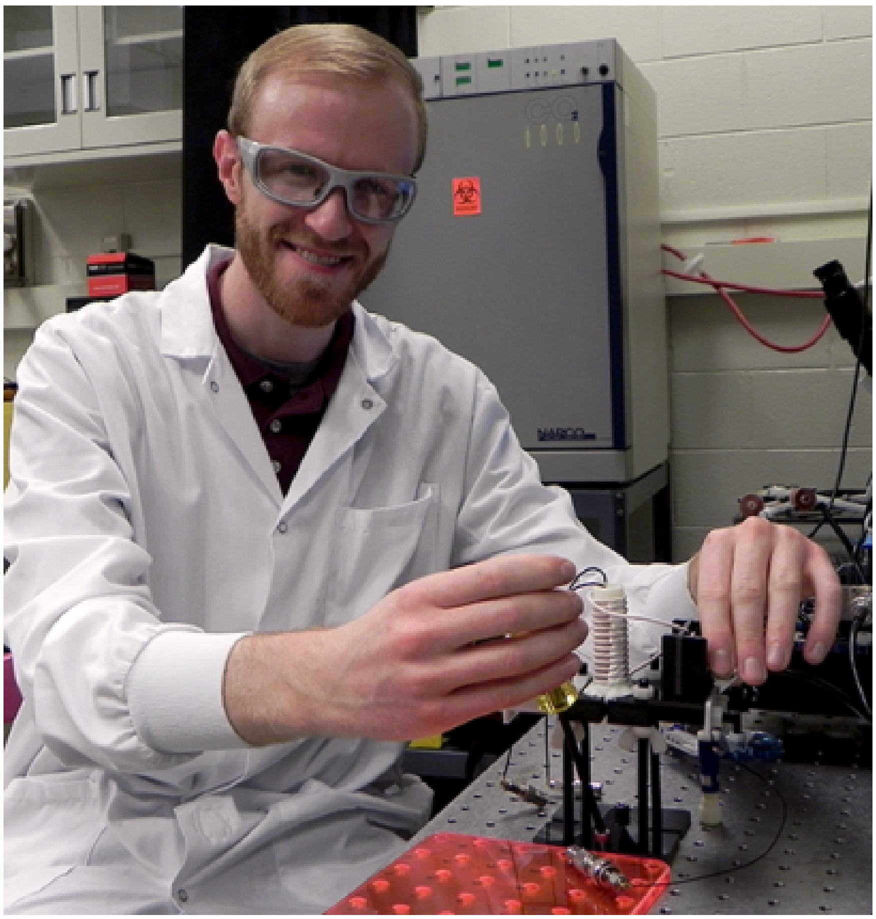

MIT graduate student Michael G. Christiansen with a magnetometry coil used to confirm heat output from magnetic iron oxide nanoparticles. Credit: Denis Paiste/Materials Processing Center

Magnetic nanoparticles don't have to be "one size fits all." Instead, individual magnetic nanoparticles can be tailored in an array of differing sizes and compositions to allow for heating them separately by varying the frequency and amplitude of an external alternating magnetic field, MIT graduate student Michael G. Christiansen and colleagues show in a recent Applied Physics Letters paper.

The new strategy, which they call magnetothermal multiplexing, has potential to be used for stimulating nerve and brain cells and targeted drug delivery.

"The novelty of our approach is to recognize that particles with sufficiently distinct magnetic properties heat up best in quite different alternating magnetic field conditions. So different, in fact, that it allows us to imagine a situation in which we can selectively heat up one type of particle without heating another type, even though they are both being exposed to the same field," Christiansen explains.

"The frequency and amplitude of the alternating magnetic field can be changed so that the roles of the different particle types being selectively heated are reversed. This is powerful because it offers a noninvasive way to independently trigger separate processes initiated by particle heating, whether it is neuromodulation, drug release, or some other desired therapeutic action," he says.

The results of Christiansen's simulation and experimental work are published in the May 26, 2014, APL paper, "Magnetically multiplexed heating of single domain nanoparticles." Christiansen's co-authors are Alex Senko, who helped collect AC magnetometry data; Ritchie Chen, who synthesized the nanoparticles; Gabriela Romero, who took transmission electron microscopy (TEM) images of nanoparticles; and senior author Polina Anikeeva, AMAX Assistant Professor in Materials Science and Engineering.

"We're trying to interface with neurons completely noninvasively by using a nanomagnetic material that can act as a transducer for neural stimulation," Anikeeva says.

Preferred magnetic direction

Ferrites, or iron oxides, which are the materials Christiansen studies, favor magnetic orientation in particular directions with respect to their crystal structure, a condition referred to as anisotropy. Their preferred magnetic directions are called "easy axes." Magnetic orientation can be influenced by applying an external magnetic field, much like a magnet can be used to deflect a compass needle, but in this case the field has to be big enough to push the orientation from one easy axis to another. If such a field is applied cyclically, pushing the orientation back and forth, the phenomenon can be illustrated graphically by a hysteresis loop, which shows the strength of the applied magnetic field required to go through a cycle from one preferred orientation to another.

In the process of this magnetic reorientation, the nanoparticles heat up and release that heat into their environment. Christiansen measured this heat output with calorimetry, which measures the change in temperature over time. He then converted that data to energy dissipation per gram of magnetic material.

Cyclical reversal

By alternating the external magnetic field, researchers cycle through the hysteresis loop for the magnetic material, producing heat. "If you have a very anisotropic particle set and you run it at a high field and low frequency, it will heat up more than another particle set with low anisotropy because the individual area of those hysteresis loops is much larger," he says. "Then if you switch to a high-frequency, low-field mode, the less anisotropic particles that didn't heat up before are going to heat up the best, because they can respond to the field with hysteresis loop areas roughly the same size as before. They cycle through these loops more rapidly at the higher frequency, so they heat up. And the other particles, which have high anisotropy, they are going to not heat up as much at high frequency and low field because their magnetization won't respond readily to a low field amplitude."

Christiansen likens the heat produced by agitation of the magnetic field to a block being rubbed on a table. A large block with a lot of friction from its weight and roughness will produce heat with a large cyclic force applied at a low frequency, but a smaller, smoother block will require less force and higher frequency to heat up. Applying a small force to a big block won't produce heat. "The magnetic field is like the force and the anisotropy is like the friction," he explains.

Stimulating neurons

One potential use of the multiplexing technique is trying to get neurons to fire by stimulating action potentials. "There are inherent biological amplification mechanisms at work," Christiansen says. "When you depolarize one tiny part of a neuronal membrane, the entire cell undergoes an action potential, because there are voltage-gated channels that are naturally present in neurons."

Magnetothermal multiplexing could be used to target different neuron types or different parts of the brain with the ability to drive them independently. "Just by changing the driving conditions of the field—that is to say, the frequency and amplitude of the alternating magnetic field—one would be able to selectively stimulate these different regions or cell types," Christiansen says.

Christiansen, 24, is entering the third year of his doctoral program in materials science and engineering this fall. As an undergraduate, Christiansen studied physics at Arizona State University, and he participated in the Summer Scholars program at MIT co-sponsored by the Materials Processing Center and the Center for Materials Science and Engineering.

Changing the chemical composition of the iron oxides, or ferrites, by adding a metal such as cobalt or manganese, also changes their response to the external magnetic field, he says: "With the addition of cobalt, ferrite becomes more anisotropic, and certain directions are very strongly preferred; manganese tends to have the opposite effect."

Confirming results

Before the paper was published, Christiansen needed to confirm the calorimetry results through an alternative set of AC magnetometry measurements, which look at the dissipated energy through the out-of-phase component of the samples' magnetization. "The big obstacle for us was that the journal reviewer wanted an additional line of evidence other than the calorimetry. So we got our review back, and we had roughly a month and a half to construct and troubleshoot this AC magnetometer," he says. Fellow graduate student Alexander Senko was brought in to help.

The AC magnetometry results confirmed his findings: "The type of multiplexing that we demonstrate in the paper is with two iron-oxide particle sets of differing diameter. One is manganese-doped. Our data shows a crossover point in the hundreds of kilohertz, so that the 25-nanometer iron oxide no longer heats up as well as the 15-nanometer iron oxide or the 15-nanometer manganese-doped iron oxide after that crossover point. The fact that they cross over is what makes multiplexing work," Christiansen explains. The MIT team has a provisional patent for the magnetothermal multiplexing.

Christiansen made a presentation on the work at the MRS Fall Meeting in Boston in December 2013. The work was funded partially by a Sanofi Biomedical Innovation Award and a Defense Advanced Research Project Agency (DARPA) Young Faculty Award.

Christiansen and colleagues are working to demonstrate the findings in a more concrete way, such as demonstrating multiplexing with drug release and other applications.

More information: "Magnetically multiplexed heating of single domain nanoparticles." M. G. Christiansen1 *Appl. Phys. Lett.* 104, 213103 (2014); dx.doi.org/10.1063/1.4879842

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