Nanostructures and Computation

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Introduction

Photonic crystals and nanophotonics employ nanoscale optical structures, on the scale of the wavelength of light, in order to produce optical phenomena far different from those in more homogeneous media—both for classical electromagnetism and for electromagnetic fields arising from quantum and thermal fluctuations. Our work has centered on four general categories of problems in nanophotonics: what new effects and devices can one achieve in such structures, how does one design devices given so many degrees of freedom and with what computational techniques, and what higher-level understanding can one develop for such complex systems.

1. Electromagnetic effects in blast-induced brain injuries

Sponsors:
Joint Improvised Explosive Device Defeat Organization (JIEDDO)
and Army Research Office (contract DAAD-19-02-D0002)
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Project staff:
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Prof. R. Radovitsky, Prof. J. D. Joannopoulos, Dr. David F. Moore (Defense and Veterans Brain Injury Center).

We are investigating how electromagnetic effects may play a role in brain injuries that are observed in soldiers exposed to improvised explosive devices (IEDs) and similar blasts, even when there is no obvious physical injury to the head, as part of a larger project studying mechanisms and mitigation of blast-induced brain injuries. In considering different possible mechanisms for brain injury, we found an unexplored mechanism—many kinds of bone are piezoelectric materials, polarizing under stress, and when an IED-scale blast wave impacts the cranial bone it may produce short-range electric fields of magnitudes and frequencies known to have neurological effects, many times larger than existing safety standards (Lee, 2011). Our initial work used theoretical modeling combined with experimental piezoelectric properties of various animal bones; efforts to form more detailed models and measure human cranial-bone properties are ongoing.

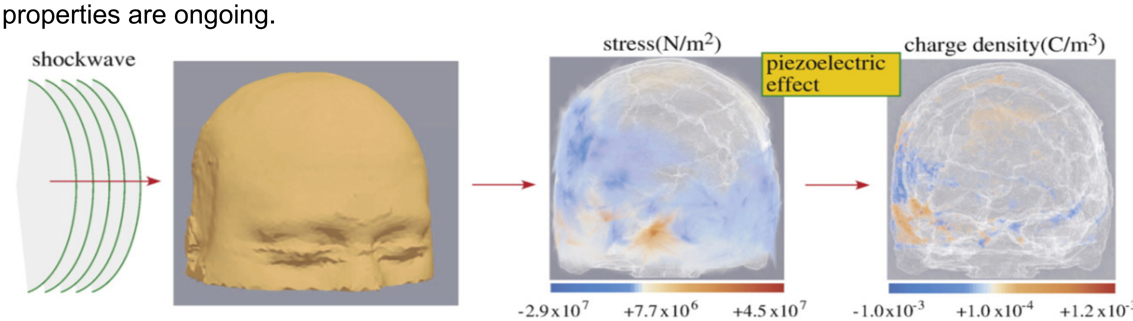

Figure 1. An explosive shockwave incident upon a head is simulated by full-head-model finite-element simulations, generating a cranial stress map (middle), as a function of time. When these stresses are combined with experimental piezoelectric constants for bone, we obtain a predicted charge density in the skull, from which an in-brain electric field can be computed.

2. Design, Modeling, and Control of Casimir Forces in Nanostructured Media

Sponsors:
DARPA (contract N66001-09-1-2070-DOD)
Army Research Office (contract W911NF-07-D004) through MIT Inst. for Soldier Nanotech. (ISN)

Project staff:
Prof. S. G. Johnson, Prof. J. D. Joannopoulos, Prof. J. White, A. W. Rodriguez, A. P. McCauley, H. Reid

Casimir forces are an interaction between uncharged objects that arise at micrometer-scale separations due to quantum vacuum-photon fluctuations. Besides their importance in basic physics research as a direct manifestation of the quantum vacuum as a measurable force, Casimir forces have important influences on cold atom trapping, thin fluid films, and potentially for future nanomechanical devices. Although they were first predicted in 1948 for parallel metallic plates, Casimir forces have proven surprisingly difficult to calculate—less than a decade ago, almost nothing was known for non-planar geometries, and no general computational methods were available. In our work, we have developed ways to directly adapt computational tools from classical electromagnetism to predict Casimir interactions. Extending these developments, in 2010 we showed how to apply powerful boundary-element methods to the Casimir problem, as well as the workhorse technique of finite-difference time-domain (FDTD) simulations. In the latter case, we developed a mathematical equivalence between Casimir calculations, which are typically performed at complex or imaginary frequencies for various reasons, and classical electromagnetism at real frequencies with artificial dissipation, forming a sort of "analog computer" in which any classical simulation (or experimental) technique can be applied off the shelf to the Casimir problem. We have also applied these and other techniques to predict forces and phenomena in a variety of new geometries, such as showing that material dispersion can be exploited to obtain stable Casimir "levitation" and non-touching microsphere clusters in fluid suspensions (fig. 2).

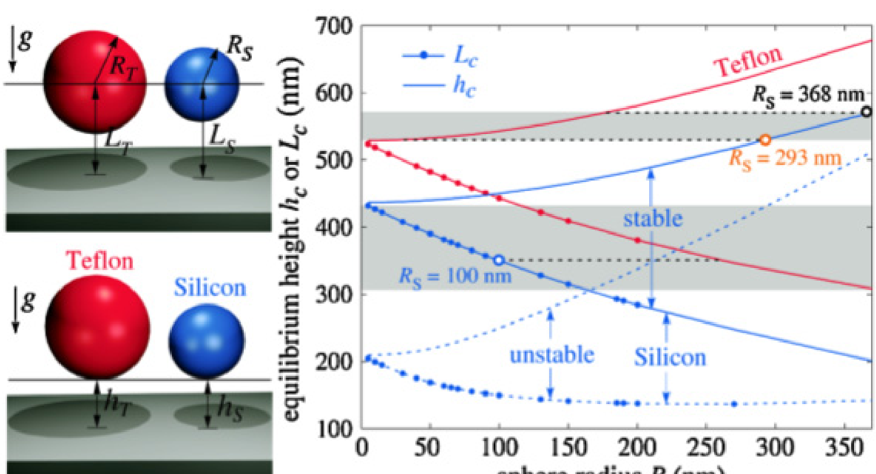

Figure 2. Appropriate materials choices allow Casimir forces to be designed so as to yield stable non-touching and "levitating" configurations, here showing the levitation height of microspheres above a gold substrate as a function of sphere radius and material.

3. Theoretical Limitations of Metamaterial Devices

Sponsors:
Army Research Office (contract W911NF-07-D004) through MIT Inst. for Soldier Nanotech. (ISN)

Project staff:
H. Hashemi, A. Oskooi, Prof. J. D. Joannopoulos, Prof. S. G. Johnson

One development in photonics that has captured the public imagination has been the idea that appropriately designed “metamaterials” can theoretically achieve electromagnetic “cloaking”—surrouding an object and making it invisible to electromagnetic radiation—as first proposed by Pendry in 2006. Although experiments have demonstrated these theoretical proposals on small scales, typically for wavelength-scale objects, we are interested in understanding the practical limitations of this and similar problems on a deeper theoretical level. Recently (Hashemi, 2010), we used a simple 1d model system to show how the difficulty of cloaking scales—in particular, we showed that the properties of the cloak materials must become more and more perfect as the size of the cloaked object increases, eventually becoming impractical. The basis for this scaling is that, at the simplest level, a cloak hiding an object above a ground plane must simulate a time delay—it must replicate the delay that the electromagnetic wave would have incurred had it bounced off an unobstructed ground—and thus falls prey to well-known limitations on delay–bandwidth and delay–loss products.

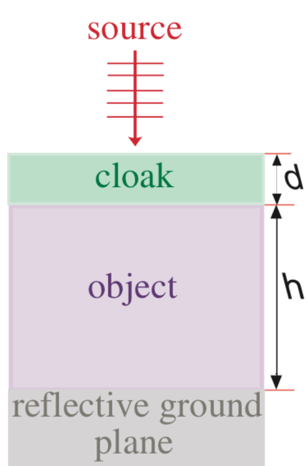

Figure 4. A simple model “cloaking” problem which illustrates the fundamental constraints on cloaking difficulty: in one dimension, a thickness-d cloak masking an object above a reflective ground plane must delay any incident wave for a time $2(d+h)/c$, the delay the wave would have incurred for bare ground. This time delay increases proportional to h, and means that the cloaking materials must be increasingly lossless and that the cloak must be increasingly thick.

Publications

Journal Articles, Published

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