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Two-dimensional graphene metamaterials, one-atom-thick optical devices envisioned

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Two University of Pennsylvania engineers have proposed the possibility of two-dimensional metamaterials. These one-atom-thick metamaterials could be achieved by controlling the conductivity of sheets of graphene, which is a single layer of carbon atoms.

Professor Nader Engheta and graduate student Ashkan Vakil, both of the Department of Electrical and Systems Engineering in Penn's School of Engineering and Applied Science, published their theoretical research in the journal *Science*.

The study of metamaterials is an interdisciplinary field of science and engineering that has grown considerably in recent years. It is premised on the idea that materials can be designed so that their overall wave qualities rely not only upon the material they are made of but also on the pattern, shape and size of irregularities, known as "inclusions," or "meta-molecules" that are embedded within host media.

"By designing the properties of the inclusions, as well as their shapes and density, you achieve in the bulk property something that may be unusual and not readily available in nature," Engheta said.

These unusual properties generally have to do with manipulating electromagnetic (EM) or acoustic waves; in this case, it is EM waves in the infrared spectrum

Changing the shape, speed and direction of these kinds of waves is a subfield of metamaterials known as "transformation optics" and may find applications in everything from telecommunications to imaging to signal processing.

Engheta and Vakil's research shows how transformation optics might now be achieved using graphene, a lattice of carbon a single atom thick.

Researchers, including many at Penn, have devoted considerable effort into developing new ways to manufacture and manipulate graphene, as its unprecedented conductivity would have many applications in the field of electronics. Engheta and Vakil's interest in graphene, however, is due to its capability to transport and guide EM waves in addition to electrical charges and the fact that its conductivity can be easily altered.

Applying direct voltage to a sheet of graphene, by way of ground plate running parallel to the sheet, changes how conductive the graphene is to EM waves. Varying the voltage or the distance between the ground plate and the graphene alters the conductivity, "just like tuning a knob," Engheta said.

"This allows you to change the conductivity of different segments of a single sheet of graphene differently from each other," he said. And if you can do that, you can navigate and manipulate a wave with those segments. In other words, you can do transformation optics using graphene."

In this marriage between graphene and metamaterials, the different regions of conductivity on the effectively two-dimensional, one-atom-thick sheet function as the physical inclusions present in three-dimensional versions.

The examples Engheta and Vakil have demonstrated with computer models include a sheet of graphene with two areas that have different conductivities, one that can support a wave, and one that cannot. The boundary between the two areas acts as a wall, capable of reflecting a guided EM wave on the graphene much like one would in a three dimensional space.

Another example involves three regions, one that can support a wave surrounded by two that cannot. This produces a "waveguide," which functions like a one-atom-thick fiber optic cable. A third example builds on the waveguide, adding another non-supporting region to split the waveguide into two.

"We can 'tame' the wave so that it moves and bends however we like," Engheta said. "Rather than playing around with the boundary between two media, we're thinking about changes of conductivity across a single sheet of graphene."

Other applications include lensing and the ability to do "flatland" Fourier transforms, a fundamental aspect of signal processing that is found in nearly every piece of technology with audio or visual components.

"This will pave the way to the thinnest optical devices imaginable," Engheta said. "You can't have anything thinner than one atom!"

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