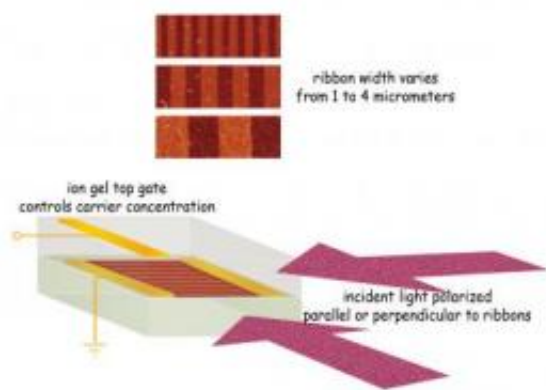


Tunable graphene device demonstrated: First tool in kit for putting terahertz light to work

September 4 2011



The graphene microribbon array can be tuned in three ways. Varying the width of the ribbons changes plasmon resonant frequency and absorbs corresponding frequencies of terahertz light. Plasmon response is much stronger when there is a dense concentration of charge carriers (electrons or holes), controlled by varying the top gate voltage. Finally, light polarized perpendicularly to the ribbons is strongly absorbed at the plasmon resonant frequency, while parallel polarization shows no such response. Credit: Lawrence Berkeley National Laboratory

Long-wavelength terahertz light is invisible – it's at the farthest end of the far infrared – but it's useful for everything from detecting explosives at the airport to designing drugs to diagnosing skin cancer. Now, for the first time, scientists at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and the University of California at Berkeley have demonstrated a microscale device made of graphene – the remarkable form of carbon that's only one atom thick –

whose strong response to light at terahertz frequencies can be tuned with exquisite precision.

"The heart of our device is an array made of [graphene](#) ribbons only millionths of a meter wide," says Feng Wang of Berkeley Lab's Materials Sciences Division, who is also an assistant professor of physics at UC Berkeley, and who led the research team. "By varying the width of the ribbons and the concentration of charge carriers in them, we can control the collective oscillations of electrons in the microribbons."

The name for such collective oscillations of electrons is "plasmons," a word that sounds abstruse but describes effects as familiar as the glowing colors in stained-glass windows.

"Plasmons in high-frequency visible light happen in three-dimensional metal nanostructures," Wang says. The colors of medieval stained glass, for example, result from oscillating collections of electrons on the surfaces of nanoparticles of gold, copper, and other metals, and depend on their size and shape. "But graphene is only one atom thick, and its electrons move in only two dimensions. In 2D systems, plasmons occur at much lower frequencies."

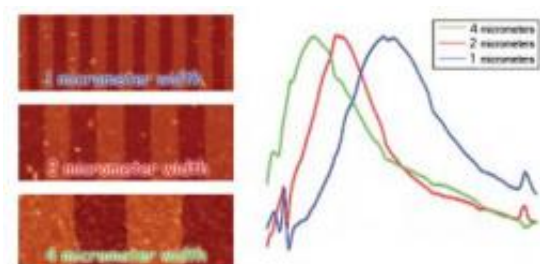
The wavelength of [terahertz](#) radiation is measured in hundreds of micrometers (millionths of a meter), yet the width of the graphene ribbons in the experimental device is only one to four micrometers each.

"A material that consists of structures with dimensions much smaller than the relevant wavelength, and which exhibits optical properties distinctly different from the bulk material, is called a metamaterial," says Wang. "So we have not only made the first studies of light and plasmon coupling in graphene, we've also created a prototype for future graphene-based metamaterials in the terahertz range."

The team reports their research in *Nature Nanotechnology*, available in advanced online publication.

How to push the plasmons

In two-dimensional graphene, electrons have a tiny rest mass and respond quickly to electric fields. A plasmon describes the collective oscillation of many electrons, and its frequency depends on how rapidly waves in this electron sea slosh back and forth between the edges of a graphene microribbon. When light of the same frequency is applied, the result is "resonant excitation," a marked increase in the strength of the oscillation – and simultaneous strong absorption of the light at that frequency. Since the frequency of the oscillations is determined by the width of the ribbons, varying their width can tune the system to absorb different frequencies of light.



At a constant carrier density, varying the width of the graphene ribbons -- from 1 micrometer (millionth of a meter) to 4 micrometers -- changes the plasmon resonant frequency from 6 to 3 terahertz. The spectra of light transmitted through the device (right) show corresponding absorption peaks. Credit: Lawrence Berkeley National Laboratory

The strength of the light-plasmon coupling can also be affected by the concentration of charge carriers – electrons and their positively charged

counterparts, holes. One remarkable characteristic of graphene is that the concentration of its charge carriers can easily be increased or decreased simply by applying a strong electric field – so-called electrostatic doping.

The Berkeley device incorporates both these methods for tuning the response to terahertz light. Microribbon arrays were made by depositing an atom-thick layer of carbon on a sheet of copper, then transferring the graphene layer to a silicon-oxide substrate and etching ribbon patterns into it. An ion gel with contact points for varying the voltage was placed on top of the graphene.

The gated graphene microarray was illuminated with terahertz radiation at beamline 1.4 of Berkeley Lab's Advanced Light Source, and transmission measurements were made with the beamline's infrared spectrometer. In this way the research team demonstrated coupling between light and plasmons that were stronger by an order of magnitude than in other 2D systems.

A final method of controlling plasmon strength and terahertz absorption depends on polarization. Light shining in the same direction as the graphene ribbons shows no variations in absorption according to frequency. But light at right angles to the ribbons – the same orientation as the oscillating electron sea – yields sharp absorption peaks. What's more, light absorption in conventional 2D semiconductor systems, such as quantum wells, can only be measured at temperatures near absolute zero. The Berkeley team measured prominent absorption peaks at room temperature.

"Terahertz radiation covers a spectral range that's difficult to work with, because until now there have been no tools," says Wang. "Now we have the beginnings of a toolset for working in this range, potentially leading to a variety of graphene-based terahertz metamaterials."

The Berkeley experimental setup is only a precursor of devices to come, which will be able to control the polarization and modify the intensity of terahertz light and enable other optical and electronic components, in applications from medical imaging to astronomy – all in two dimensions.

More information: "Graphene plasmonics for tunable terahertz metamaterials," by Long Ju, Baisong Geng, Jason Horng, Caglar Girit, Michael Martin, Zhao Hao, Hans A. Bechtel, Xiaogan Liang, Alex Zettl, Y. Ron Shen, and Feng Wang, appears in [Nature Nanotechnology](#).

Provided by Lawrence Berkeley National Laboratory

Citation: Tunable graphene device demonstrated: First tool in kit for putting terahertz light to work (2011, September 4) retrieved 10 April 2024 from <https://phys.org/news/2011-09-tunable-graphene-device-tool-kit.html>

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