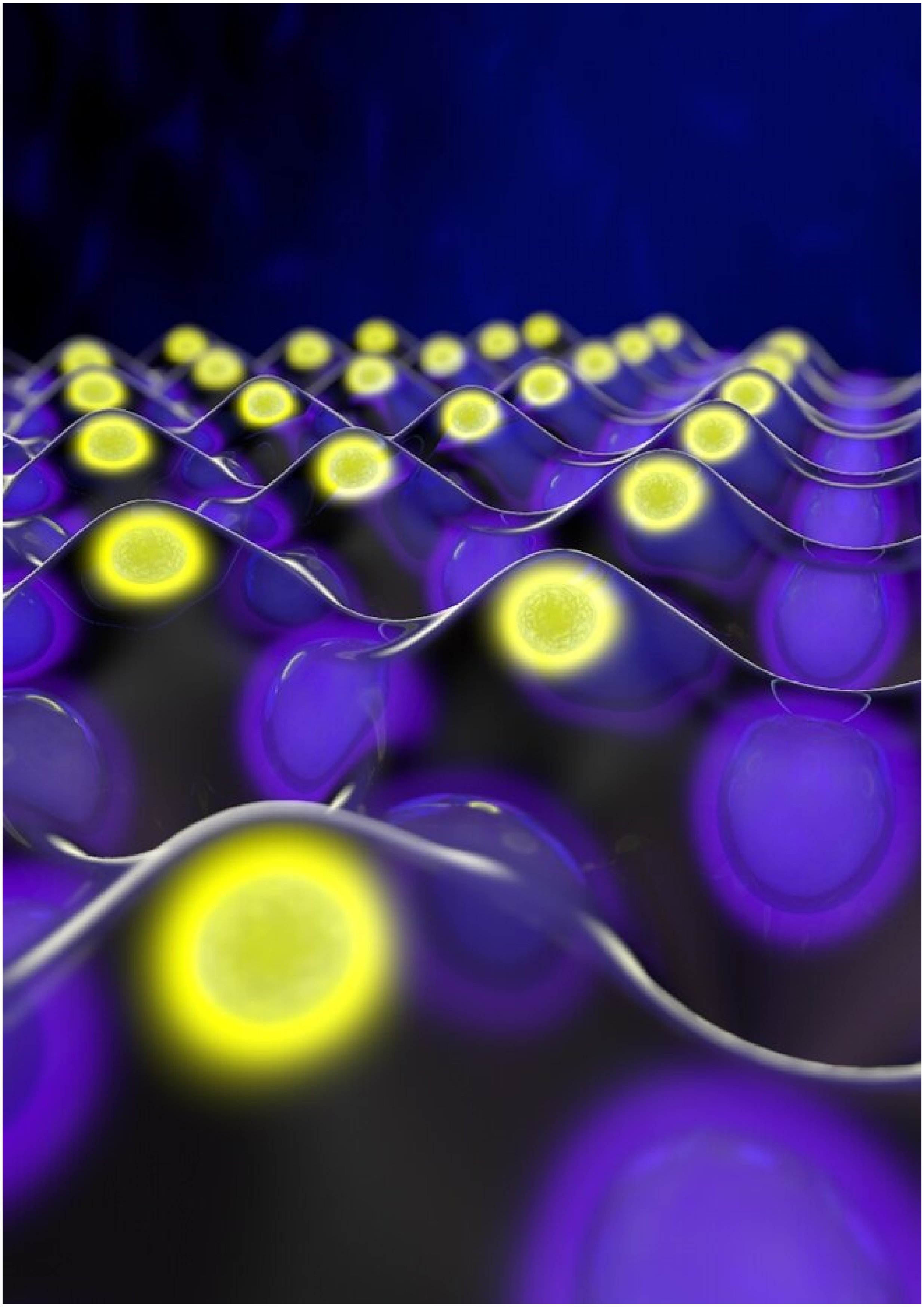
Laser takes pictures of electrons in crystals

July 1 2020, by E. Goulielmakis, H. Lakhotia, H.-Y. Kim, M. Zhan, S. Hu, S. Meng



Electrons in the crystal of calcium fluoride. Credit: Christian Hackenberger/University of Rostock

Microscopes of visible light allow scientists to see tiny objects such living cells. Yet, they cannot discern how electrons are distributed among atoms in solids. Now, researchers with Prof. Eleftherios Goulielmakis of the Extreme Photonics Labs at the University of Rostock and the Max Planck Institute of Quantum Optics in Garching, Germany, along with coworkers of the Institute of Physics of the Chinese Academy of Sciences in Beijing, have developed a new type of a light microscope, called the Picoscope, that overcomes this limitation.

The researchers used powerful laser flashes to irradiate thin films of crystalline materials. These laser pulses drove crystal electrons into a fast wiggling motion. As the electrons bounced off the surrounding electrons, they emitted radiation in the extreme ultraviolet part of the spectrum. By analyzing the properties of this radiation, the researchers composed pictures that illustrate how the electron cloud is distributed among atoms in the crystal lattice of solids with a resolution of a few tens of picometers, which are billionths of a millimeter. The experiments pave the way for a new class of laser-based microscopes that could allow physicists, chemists, and material scientists to peer into the details of the microcosm with unprecedented resolution and to understand and eventually control the chemical and the electronic properties of materials.

For decades, scientists have used flashes of laser light to understand the inner workings of the microcosm. Such lasers flashes can now track ultrafast microscopic processes inside solids. Still, they cannot spatially resolve electrons, i.e., see how electrons occupy the minute space among atoms in crystals, or how they form the chemical bonds that hold atoms together. Ernst Abbe discovered the reason more than a century ago. Visible light can only discern objects commensurable in size to its wavelength, which is approximately few hundreds of nanometers. But to see electrons, the microscopes have to increase their magnification power by a few thousand times.

To overcome this limitation, Goulielmakis and coworkers took a different path. They developed a microscope that works with powerful laser pulses. They dubbed their device a Light Picoscope. "A powerful laser pulse can force electrons inside crystalline materials to become the photographers of the space around them," said Harshit Lakhotia, a researcher of the group.

When the laser pulse penetrates inside the crystal, it can grab an electron and drive it into a fast wiggling motion. "As the electron moves, it feels the space around it, just like your car feels the uneven surface of a bumpy road," said Lakhotia. When the laser-driven electrons cross a bump made by other electrons or atoms, it decelerates and emits radiation at a frequency much higher than that of the lasers. "By recording and analyzing the properties of this radiation, we can deduce the shape of these minute bumps, and we can draw pictures that show where the electron density in the crystal is high or low," said Hee-Yong Kim, a doctoral researcher in the Extreme Photonics Labs. "Laser Picoscopy combines the capability of peering into the bulk of materials, like X-rays, and that of probing valence electrons. The latter is possible by scanning tunneling microscopes but only on surfaces."

Sheng Meng, from the Institute of Physics, Beijing, and a theoretical solid-state physicist in the research team, said, "With a microscope capable of probing, the valence electron density we may soon be able to benchmark the performance of computational solid-state physics tools.

We can optimize modern, state-of-the-art models to predict the properties of materials with ever finer detail. This is an exciting aspect that laser picoscopy brings in."

Now, the researchers are working on developing the technique further. They plan to probe electrons in three dimensions and further benchmark the method with a broad range of materials including 2-D and topological materials. "Because laser picoscopy can be readily combined with time-resolved laser techniques, it may soon become possible to record real movies of electrons in materials. This is a long-sought goal in ultrafast sciences and microscopies of matter," Goulielmakis said.

More information: Laser picoscopy of valence electrons in solids, *Nature*, DOI: 10.1038/s41586-020-2429-z , www.nature.com/articles/s41586-020-2429-z

Provided by University of Rostock