Snapshots at 1/1,000,000,000,000 of a second

BY BREEHAN GERLEMAN LUCCHESI

Ames Laboratory physicist Jigang Wang is revealing the mysteries of new materials using ultra-fast laser spectroscopy. Wang likens the technique to high-speed photography where many quick images reveal subtle movements and changes inside the materials. Seeing these dynamics is one emerging strategy to better understanding how new materials work, so that we can use them to enable new energy technologies.

Wang and his colleagues recently used ultra-fast laser spectroscopy to examine and explain the mysterious electronic properties of iron-based superconductors.

Superconductors are materials that, when cooled below a certain temperature, display zero electrical resistance, a property that could someday make possible lossless electrical distribution. Superconductors start in a "normal," often magnetic, state and then transition to a superconducting state when they are cooled to a certain temperature.

What is still a mystery is what goes on in materials as they transform from normal to superconducting. And this "messy middle" area of superconducting materials' behavior holds richer information about the why and how of superconductivity than do the stable areas.

"The stable states of materials aren't quite as interesting as the crossover region when it comes to understanding materials' mechanisms because everything is settled and there's not a lot of action. But, in this crossover region to superconductivity, we can study the dynamics, see what goes where and when, and this information will tell us a lot about the interplay between superconductivity and magnetism," says Wang, who is also an associate professor of physics and astronomy at Iowa State University.

But the challenge is that in the crossover region, all the different sets of a material's properties that scientists examine, like its magnetic order and electronic order, are all coupled. In other words, when there's a change to one set of properties, it affects all the others. So, tracing what individual changes and properties are dominant is difficult.

Wang and the team use ultra-fast laser spectroscopy to "see" the tiny actions in materials. In ultra-fast laser spectroscopy, scientists apply a pulsed laser to a material sample to excite particles within the sample. Some of the laser light is absorbed by the material. Other time-delayed light pulses subsequently hit the material and can be used to take super-fast "snapshots" of what is going on in the material following the laser pulse. The snapshots are replayed afterward like a stop-action movie. One decisive advantage of this approach is the capability to shoot the first frame in less than one trillionth of a second.

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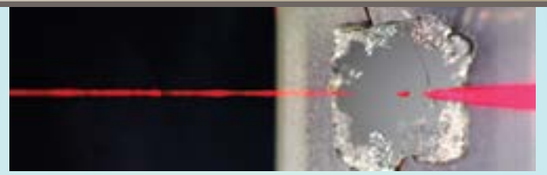
The technique is especially well suited to understanding the crossover region of iron-arsenide based superconductors materials because the laser excitation alters the material so that different properties of the material are distinguishable from each other in time. With the help of successive "snapshots and replays," even the most subtle evolutions in the materials' properties can show their secrets.

"Ultra-fast laser spectroscopy is a new experimental tool to study dynamic, emergent behavior in complex materials such as these iron-based superconductors," says Wang. "Specifically, we answered the pressing question of whether an electronically-driven nematic order exists as an independent phase in iron-based superconductors, as these materials go from a magnetic normal state to superconducting state. The answer is yes. This is important to our overall understanding of how superconductors emerge in this type of materials."

Wang and his colleagues have also used ultra-fast laser spectroscopy to demonstrate broadband terahertz wave generation using deep-sub-wavelength metamaterials emitters, quantum ultrafast magnetic switching, and stimulated emission of Dirac fermions in graphene monolayers.

"Ultra-fast laser spectroscopy is still a relatively new characterization technique," says Wang. "My goal is to help merge the field with the traditional materials research community, which may orchestrate a new paradigm for quantum materials discovery, understanding and control."



Ames Laboratory scientists use ultra-fast laser spectroscopy to "see" tiny actions in real time in materials. Scientists apply a pulse laser to a sample to excite the material. Some of the laser light is absorbed by the material, but the light that passes through or reflected from the material can be used to take super-fast "snapshots" of what is going on in the material following the laser pulse.

More is Different

"If there's a theme to my research, it's small things and complex things," says Jigang Wang.

His fascination with the small started as an undergraduate physics student.

"I was interested in the scientific philosophy of reductionism: that to understand phenomena, we have to go to the small, smaller and smallest until we find and understand the most fundamental particles. That by understanding one small piece, we can better understand the whole," says Wang.

The interest led him to study very small semiconductor nanostructures in graduate school and carbon nanotubes as a postdoctoral researcher. But, along the way, Wang turned to physicist Philip Warren Anderson's concept of "more is different," which emphasizes the importance of complexity – how small particles organize themselves and how the organization creates different levels of principles that help explain the whole.

"We see that this concept cuts across different subdisciplines of physics, biology, chemistry, and applied science, and, of course, also in materials science, like superconductivity or magnetism," says Wang. "You have these fascinating functions from these many particles bound by simple interactions. I study these complex systems: their dynamics, or how they change; how certain changes in the systems correlate to other changes to drive cooperative behaviors; and their nonlinearity, or how the output from a system is different from the input, to build functionalities."

"More is indeed different," he adds. "And my goal using femto-second laser spectroscopy is to build our understanding how these complex quantum materials work by revealing their organization principles from nanoscale to mesoscale and how we can harness their properties for energy applications."