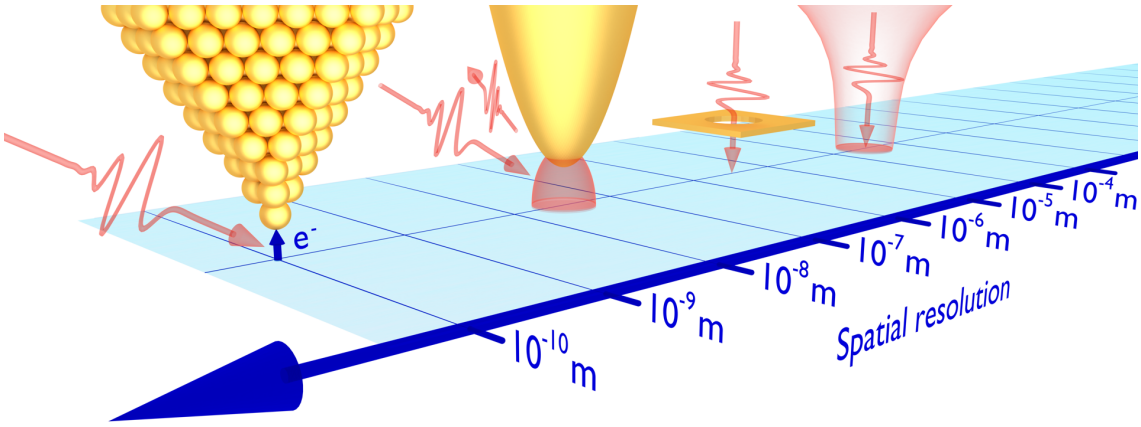
Watching atoms move with terahertz scanning probe microscopy

Tyler L. Cocker

Michigan State University, East Lansing, MI 48824, USA

The terahertz range of the electromagnetic spectrum hosts material excitations that are particularly important for nanotechnology, such as the collective motion of charges, spins, and ions. These excitations are often studied with terahertz time-domain spectroscopy, which directly measures the oscillating electric field of a terahertz light pulse and relates it to key material processes through the light-matter interaction[1]. Coherent detection of terahertz fields can even reveal dynamics faster than a terahertz oscillation cycle[2,3]. However, conventional terahertz time-domain spectroscopy measurements average the sample response over macroscopic length scales due to the diffraction limit. Experimental techniques have been developed based on scanning probes to improve the spatial resolution of terahertz science[4,5], as visualized in Figure 1. On the far left of Figure 1, lightwave-driven scanning tunneling microscopy[6-10] reaches the atomic limit by coherently controlling quantum tunneling of electrons between a tip and sample with the oscillating terahertz field. At present, it is the only experimental technique capable of simultaneous atomic spatial resolution and ultrafast temporal resolution.

In this talk, I will first introduce the central concepts of lightwave-driven microscopy and then show how it can be used to perform atomic-scale terahertz time-domain spectroscopy[11], visualize electron densities in single molecules[6,9], and even control topological phase transitions in materials.



References

[1] S. H. Lee *et al.*, Adv. Opt. Mater. (2024).
[2] M. Eisele *et al.*, Nat. Photon. **8**, 241 (2014).
[3] M. Plankl *et al.*, Nat. Photon. **15**, 594 (2021).
[4] T. L. Cocker *et al.*, Nat. Photon. **15**, 558 (2021).
[5] J. Lloyd-Hughes *et al.*, J. Phys.: Condens. Matter **33**, 353001 (2021).
[6] T. L. Cocker *et al.*, Nat. Photon. **7**, 620 (2013).
[7] T. L. Cocker *et al.*, Nature **539**, 263 (2016).
[8] V. Jelic *et al.*, Nat. Phys. **13**, 591 (2017).
[9] S. E. Ammerman *et al.*, Nat. Commun. **12**, 6794 (2021).
[10] S. E. Ammerman *et al.*, Phys. Rev. B **105**, 115427 (2022).
[11] V. Jelic *et al.*, Nat. Photon. (2024).

Tyler L. Cocker, Michigan State University

Tyler Cocker is an Assistant Professor and Jerry Cowen Endowed Chair in Experimental Physics in the Department of Physics and Astronomy at Michigan State University, where he has been since 2018. Before he started his current position, Tyler spent five years working with Prof. Rupert Huber at the University of Regensburg in Germany, first as a postdoctoral researcher, then as an Alexander von Humboldt Fellow, and finally as a Junior Group Leader. Tyler did his Ph.D. work with Prof. Frank Hegmann at the University of Alberta in Canada, graduating in 2012. His undergraduate degree is from the University of Victoria in Canada, which is on the Pacific coast near his hometown island. In his research career, Tyler has pioneered ultrafast microscopy techniques using terahertz light, and received the 2021 Young Scientist Award from the Infrared, Millimeter, and Terahertz Wave Society, as well as a 2021 Young Investigator Award from the Army Research Office.