Toward Quantum Optics with Free Electrons

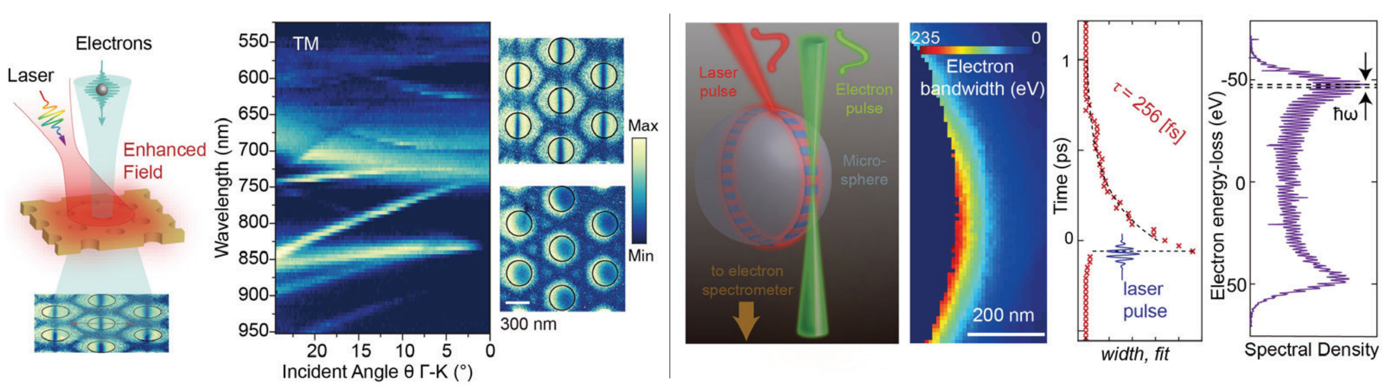
Electron microscopy and spectroscopy are ubiquitous in the investigation of materials and structures, providing a spatial resolution down to the atomic scale. Novel approaches with transmission electron microscopes, such as photo-induced near-field electron microscopy (PINEM),[1] use electron beams to characterize optical fields in matter with deep subwavelength resolution. Much effort in electron nanoscopy of optical fields has been directed toward plasmons in metals and other absorbing materials, due to the stronger interaction provided by their collective electronic resonances. Nevertheless, the weak coupling between free electrons and light remains the limiting factor that has prevented access to versatile electron–photon physics, such as the entanglement of individual photons and electrons.[2]

This year, we demonstrated that photonic cavities can increase the coupling strength of electrons and light by more than an order of magnitude.[3,4] We investigated a photonic-crystal cavity (PhC) and an optical whispering-gallery-mode (WGM) microresonator, two widely used types of photonic cavities.

In the PhC, the enhancement manifests as a record efficiency of the interaction, requiring only picojoule pulse energies.[3] We optically pumped the PhC, and used the electron probe to map its modes spatially and temporally, while also retrieving the full optical band structure. In the WGM resonator, we efficiently in-coupled the laser to a microsphere cavity mode and achieved extreme numbers of photon quanta coherently exchanged with each electron.[4] Utilizing a few-nanometer-wide electron probe, we analyzed the local WGM spectral density and mapped its field distribution. We also used the electrons to probe the ringdown time of both photonic cavities.

The extremely efficient electron–light coupling resulted in the electron simultaneously absorbing and emitting hundreds of photons. The result is a coherent electron energy comb that extends over hundreds of electron volts.[4,5] These effects are achieved by a dramatic extension of the interaction length and duration,[4] combined with precise matching of the electron velocity and light phase velocity over hundreds of microns along the electron trajectory.[5]

Future high-*Q* cavities, combined with phase-matched interactions, will enable strong electron–light coupling and quantum optics of free electrons.[2] Microresonators and other photonic cavities represent the first of many key building blocks that could allow for integration of electron beams with advanced photonic technology. This, we believe, will enhance the scopes of both photonics and analytical electron microscopy. OPN



Cavity-enhanced coupling of relativistic coherent electrons and light. Left: Electron–light interaction in a photonic-crystal slab, electron mapped optical band structures, and subwavelength imaging on Bloch modes in ultrafast electron microscopy. Right: Localized electron probe interaction with whispering-gallery modes in a microsphere, spatial and temporal mapping of the modes, and high-order photon exchanges that coherently broaden each electron's energy bandwidth.

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