One-of-a-kind microscope enables breakthrough in quantum science

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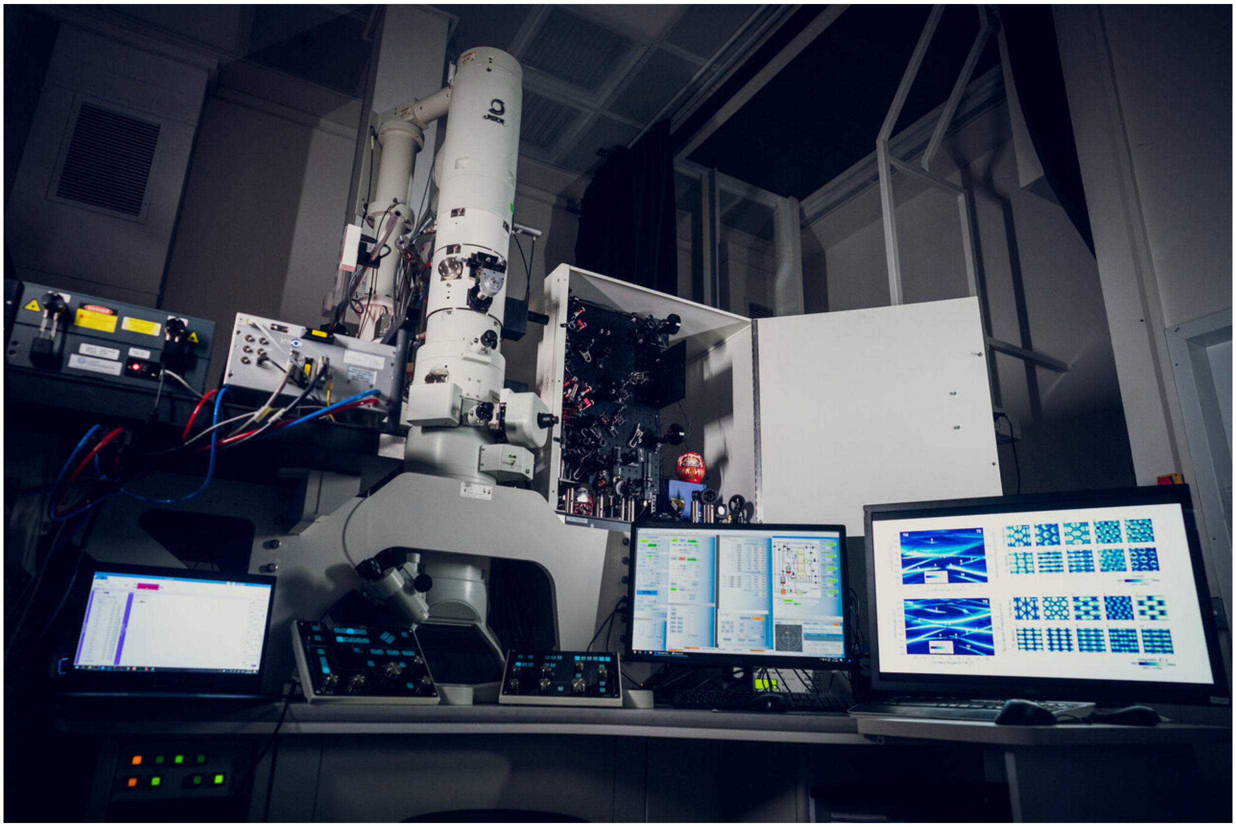


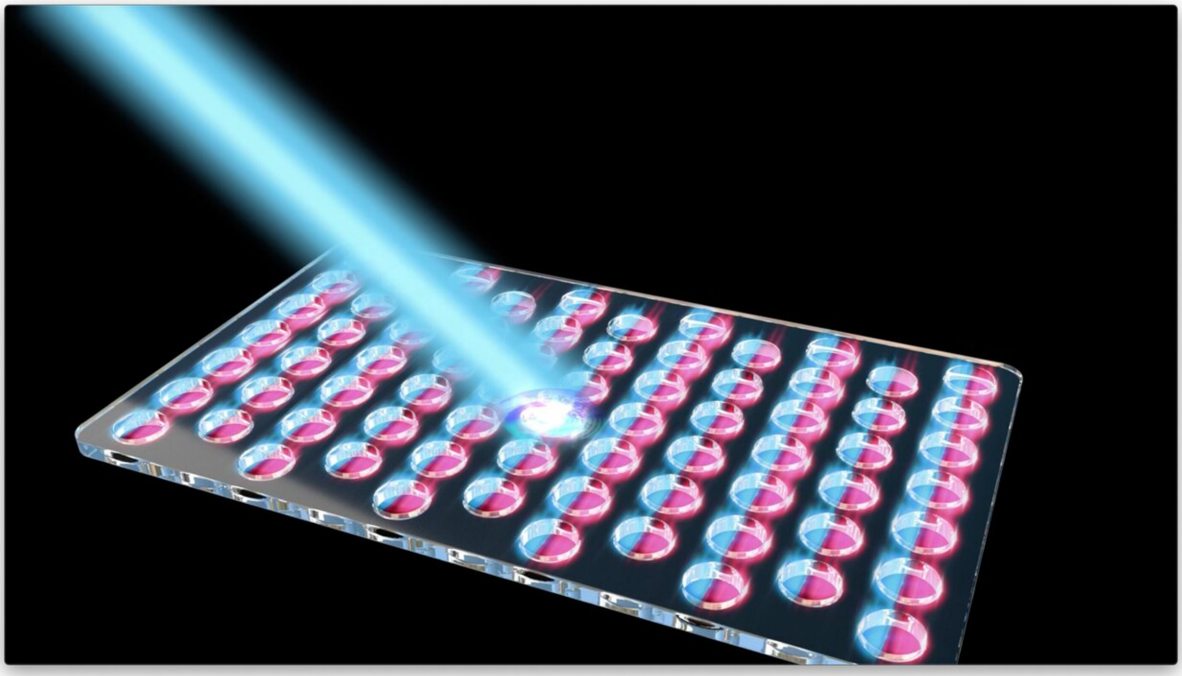
The quantum microscope. Credit: American Technion Society

Technion Professor Ido Kaminer and his team have made a dramatic breakthrough in the field of quantum science: a quantum microscope that records the flow of light, enabling the direct observation of light trapped inside a photonic crystal.

Their research, "Coherent Interaction Between Free Electrons and a Photonic Cavity," was published in *Nature*. All the experiments were performed using a unique ultrafast transmission electron microscope at the Technion-Israel Institute of Technology. The microscope is the latest and most versatile of a handful that exist in the scientific world.

"We have developed an electron microscope that produces, what is in many respects, the best near- field optical microscopy in the world. Using our microscope, we can change the color and angle of light that illuminates any sample of nano materials and map their interactions with electrons, as we demonstrated with photonic crystals," explained Prof. Kaminer. "This is the first time we can actually see the dynamics of light while it is trapped in nano materials, rather than relying on computer simulations," added Dr. Kangpeng Wang, a postdoc in the group and first author on the paper.

All of the experiments were performed on the ultrafast transmission electron microscope in the Robert and Ruth Magid Electron Beam Quantum Dynamics Laboratory headed by Prof. Kaminer. He is a faculty member in the Andrew and Erna Viterbi Faculty of Electrical Engineering and the Solid State Institute, and affiliated with the Helen Diller Quantum Center and the Russell Berrie Nanotechology Institute. The research team also includes: Dr. Kangpeng Wang, Raphael Dahan, Michael Shentcis, Dr. Yaron Kauffmann, Adi Ben-Hayun, Ori Reinhardt, and Shai Tsesses.



The photonic crystal traps light in a different pattern for each color of light. Credit: Songdi Technology (Beijing) Co. Ltd.

Far-reaching Applications

This breakthrough is likely to have an impact on numerous potential applications, including the design of new quantum materials for storing quantum bits with greater stability. Similarly, it can help improve the sharpness of colors on cell phones and other kinds of screens.

"It will have an even wider impact once we investigate more advanced nano/quantum materials. We have an extremely high-resolution microscope and we are starting to explore the next stages," Prof. Kaminer elaborated. "For example, the most advanced screens in the world today use QLED technology based on quantum dots, making it possible to control color contrast at a much higher definition. The challenge is how to improve the quality of these tiny quantum dots on large surfaces and make them more uniform. This will enhance screen resolution and color contrast even more than current technologies enable."

A New Kind of Quantum Matter

The ultrafast transmission electron microscope in Prof. Kaminer's AdQuanta lab has an acceleration voltage that varies from 40 kV to 200 kV (accelerates electrons to 30-70% the speed of light), and a laser system with sub 100 femtosecond pulses at 40 Watts. The ultrafast electron transmission microscope is a femtosecond pump-probe setup that uses light pulses for exciting the sample and electron pulses for probing the sample's transient state. These electron pulses penetrate the sample and image it. The inclusion of multidimensional capabilities in one setup is extremely useful for full characterization of nano-scale objects.

At the heart of the breakthrough lies the fact that advances in the research of ultrafast free-electron-light interactions have introduced a new kind of quantum matter—quantum free-electron "wavepackets." In the past, quantum electrodynamics (QED) studied the interaction of quantum matter with cavity modes of light which has been crucial in the development of the underlying physics that constitutes the infrastructure of quantum technologies. However, all experiments to date have only focused on light interacting with bound-electron systems—such as atoms, quantum dots, and quantum circuits—which are significantly limited in their fixed energy states, spectral range, and selection rules. Quantum free-electron wavepackets, however, have no such limits. Despite multiple theoretical predictions of exciting new cavity effects with free electrons, no photonic cavity effect has previously been observed for free electrons, due to fundamental limits on the strength and duration of the interaction.

Prof. Kaminer and his team have developed an experimental platform for the multidimensional study of free-electron interactions with photons at the nanoscale. Their unique microscope achieved record near-field optical maps by utilizing the quantum nature of electrons, which were verified by observing Rabi oscillations of the electron spectrum that cannot be explained by pure classical theory.

More efficient free-electron-cavity-photon interactions could allow strong coupling, photon quantum state synthesis, and novel quantum nonlinear phenomena. The field of electron microscopy and additional areas of free-electron physics may gain from the fusion with photonic cavities, enabling low-dose, ultrafast electron microscopy of soft matter or other beam-sensitive materials.

Prof. Kaminer hopes that the microscope will serve the wider Technion community in other research fields. "I would like to nurture interdisciplinary collaboration," he noted.

More information: Kangpeng Wang et al. Coherent interaction between free electrons and a photonic cavity, *Nature* (2020). DOI: 10.1038/s41586-020-2321-x

Provided by American Technion Society