structural basis to skill learning and reopen the field for new theories of memory formation. ■

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MICROSCOPY

Photons and electrons team up

F. Javier García de Abajo

An imaging technique has been demonstrated that blends the principles of conventional light and electron microscopy. It renders images with nanometre and femtosecond space–time resolution.

How can we probe light fields in the vicinity of nanostructures? This question is becoming increasingly relevant as the confinement and steering of light at the nanoscale are gathering momentum in applications such as optical sensing and information processing. On page 902 of this issue, Barwick *et al.*[1] provide a practical answer to this question. They report a microscopy technique that probes such fields by focusing both light and electron pulses on the nanostructures under study.

In the new imaging technique, which Barwick and colleagues baptized photon-induced near-field electron microscopy (PINEM), a specially designed electron microscope is used to project magnified images of nanostructures in much the same way as an overhead projector forms images of slides from a light beam passing through them. In PINEM, the beam is made of electrons and the role of the slides in the projector is played by light trapped in the vicinity of the samples (see Fig. 4 on page 905).

The term 'trapped' means that the light waves do not propagate and decay exponentially in intensity with distance from the sample. Unlike freely propagating light, this trapped light, called an evanescent light field, can interact efficiently with the electrons, which gain or lose energy through the absorption or emission of light quanta (photons). By means of energy-filtering, the microscope subsequently selects and collects only those electrons that have undergone energy gain, forming images in a process that retains the sub-nanometre spatial resolution that is characteristic of conventional transmission electron microscopes. The number of collected electrons is proportional to the strength of the evanescent field.

Travelling at 70% of the speed of light, the electrons used by Barwick *et al.*[1] spend only a fraction of a femtosecond (1 femtosecond is 10^{-15} seconds) near their 100-nanometre-thick samples (carbon nanotubes or silver nanowires). To observe a sizeable, and useful, electron–light interaction during such a short time interval requires intense light fields. In their experiment, the authors achieved high-intensity fields by using two synchronized femtosecond light pulses: one of the pulses was directed to the microscope's electron gun, which converted it into an electron pulse via photoemission; the other, with a peak intensity of about 10–100 gigawatts per square centimetre, was aimed at the nanostructure and was capable of producing multiple-photon absorption (or emission) events by each passing electron — up to eight photons, as the authors report[1]. By design, both pulses have a similar temporal duration, of the order of a few hundred femtoseconds (this duration defines the time resolution of PINEM), and their relative delay in the time of arrival at the sample was controlled with femtosecond precision through the difference in optical path length between the two original light pulses.

Light–electron interactions similar to those seen in Barwick and co-workers' experiment have been observed previously — for example, when electrons pick up thermal phonons (quanta of atomic lattice vibrations) in insulator films[2] or plasmons (quanta of collective oscillations of conduction electrons) from a metal surface[3], or when electrons interact with evanescent fields reflected from an illuminated diffraction grating[4]. Barwick *et al.* are the first to exploit such interactions to image an evanescent light field in the vicinity of a nanostructure, and they accomplish that with nanometre and femtosecond space–time resolution (see Fig. 2 on page 903).

Evanescent light fields have been probed previously with near-field optical microscopes[5] that rely on scanning a subwavelength-sized tip over the sample to form images. These microscopes can yield femtosecond time resolution but are limited by the size of the tip to tens of nanometres in spatial resolution. In addition, the tip can produce undesired artefacts in the images. By contrast, Barwick and colleagues' PINEM technique achieves the sub-nanometre spatial resolution that electron microscopes do. What's more, the electrons constitute a relatively 'clean' probe: moderate electron-beam intensities cause only marginal perturbations in the sample, thus allowing faithful imaging.

Barwick *et al.* demonstrated their PINEM technique for light pulses lasting about 220 femtoseconds, and observed the real-time evolution of the evanescent field that mimics the light pulses themselves. With 220-femtosecond pulses, one could also investigate the dynamics of optical excitations in the sample that have comparable or larger lifetimes, such as certain long-lived photon states that occur in insulating structures (for example, 'Mie modes' in silicon cavities). However, impressive as it is, the technique needs to be adapted for shorter light pulses that can follow the ultrafast dynamical optical response of many nanostructures of interest, such as metallic nanoparticles whose plasmons typically live for only a few tens of femtoseconds.

The propagation of light fields along the surface of a nanostructure is a key ingredient of nanophotonic devices, which carry and process optical signals[6]. The PINEM technique could be improved to study such propagation by sampling the evanescent decay of such fields along the direction perpendicular to the sample surface. This and other developments will surely show that, with Barwick and colleagues' electrons gaining energy, the scientific community will also gain new means of observing the nanoworld. ■

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