Optical metrology with sub-atomic resolution

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Abstract: The relative positions of nanostructures can be measured with picometric resolution using scattering of free electrons or topologically structured light at sharp edges of the structures. Through artificial intelligence-enabled analysis of scattered coherent light, sub-atomic resolution is achievable in single-shot measurements.

Motion at the nano- to atomic scale is of growing technological importance and fundamental interest, in nano-electro-mechanical systems (NEMS), advanced materials (e.g. nanowires, 2D materials), mechanically reconfigurable photonic metamaterials; and in the study of systems governed by Van der Waals and Casimir forces, and quantum phenomena. However, there are no routinely available technologies for quantifying and spatially mapping fast, complex movements of picometric amplitude in nanostructures. We show how the spectrally resolved detection of scattering from a tightly-focused free-electron beam, or deep learning-enabled analysis of scattering from a superoscillatory light field, incident on the sharp edges of a nano-object can provide measurements of position and displacement at the picoscale (Fig. 1).

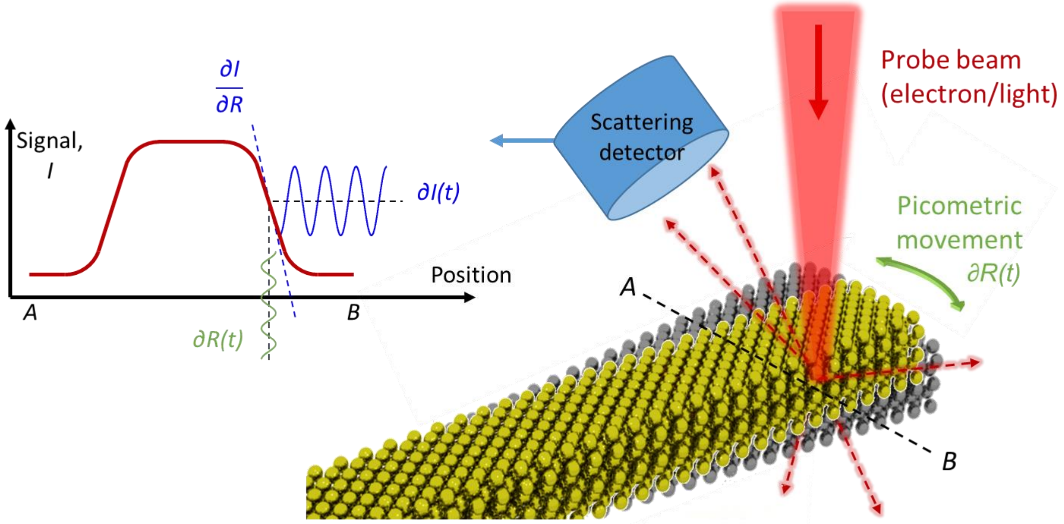

Fig. 1 Edge-scattering detection of picometric displacement. At the sharp edges of a nano-object, high gradients in the scattered (electron or optical) signal enable transduction of small movements. Small time-dependent displacements $\partial R(t)$ of the object translate to time-dependent changes $\partial I(t)$ in signal – for example, the secondary electron current (from an incident free-electron probe beam) or diffraction pattern (from an incident structured light field).

For a range of nano/microstructures, from simple cantilevers to photonic metamaterials and MEMS comb-drive actuators, we report on measurements of thermal (cf. Brownian) motion amplitudes down to a noise-equivalent displacement level of 1 pm/Hz$^{1/2}$, and the mapping of driven-motion oscillatory 'mode shapes' with spatial (SEM imaging) resolution far beyond the diffraction limit applicable to optical vibrometry techniques.

We report on the first observation of short-timescale ballistic motion of a cantilever cut from a free-standing gold nano-membrane, driven by fluctuation in thermal flexural phonon numbers in the membrane: over intervals <10 µs, the membrane is found to move ballistically, at an average constant velocity of ~300 µm/s, while Brownian-like dynamics emerge for longer observation times. These measurements provide a first experimental verification of thermal equipartition theorem and the Maxwell-Boltzmann velocity distribution for flexural motion.

And we report on optical measurement of nanostructural displacements with picometric resolution: Deep learning-enabled analysis of single-shot light scattering from an incident superoscillatory focal spot, a wavelength λ of 488 nm, yield displacement resolution of <100 pm, i.e. <λ/5000.