Hyperspectral Visualization of Picometric Motion

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The motion of nanostructures can be measured with picometric resolution using scattering of free electrons at sharp edges of the structures.

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 incident on the sharp edges of a nano-object can provide for quantitative 3D visualization of motion at the picoscale.

For a range of nano/microstructures, from simple cantilevers to photonic metamaterials and MEMS comb-drive actuators, we demonstrate 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 also report on the first observation of short-timescale ‘ballistic’ thermal motion in the flexural mode of a nanomembrane cantilever, driven by thermal fluctuation of 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. Access to the ballistic regime provides verification of the equipartition theorem and Maxwell-Boltzmann statistics for flexural modes and presents opportunities in fast thermometry and mass sensing.