Picophotonic Localization Metrology at MHz Frame Rates: Beyond Brownian Motion

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Movements of a suspended microwire exhibiting flexural phononic thermal motion in vacuum can be tracked optically at length and timescales which Einstein once envisaged as immeasurably small, revealing the transition from stochastic to ballistic motion.

Flexural deformations and modes of oscillation are now understood to be of fundamental importance to the thermal, optical, electrical, and mechanical properties of 2D materials, and the functionality of a growing range of micro-electro/opto-mechanical technologies. Yet the phonon-dominated dynamics of freestanding films, nanomembranes, nanowires, and cantilevers remain underexplored through lack of techniques for quantifying their short–timescale nano/picoscale motion. Far field optical metrology techniques based on imaging, for example, are generally constrained in spatial resolution by the diffraction limit (~100s nm at optical wavelengths) and/or temporal resolution by low camera frame rates (typically ~10s Hz). Here, we demonstrate that a deep learning-enabled analysis of transmission scattering patterns captured at MHz frame rates can facilitate direct tracking of microwire Brownian motion, approaching the ballistic regime, with positional sensitivity better than 200 pm.

As a test object, we employ a 100 μm-long, free-standing double-clamped microwire fabricated by focused ion beam milling on 50 nm-thick silicon nitride membrane coated with 70 nm gold (Fig. 1a). The microwire is illuminated with laser light at a wavelength λ = 640 nm and transmission scattering patterns are recorded by a high-speed camera running at up to 10^6 frames per second. A convolutional neural network is trained (using 18,000 scattering patterns for known, electrostatically controlled positions of the wire), to enable subsequent recording of time-series data for thermal (i.e. uncontrolled, random) fluctuations of is position (Fig. 1b).

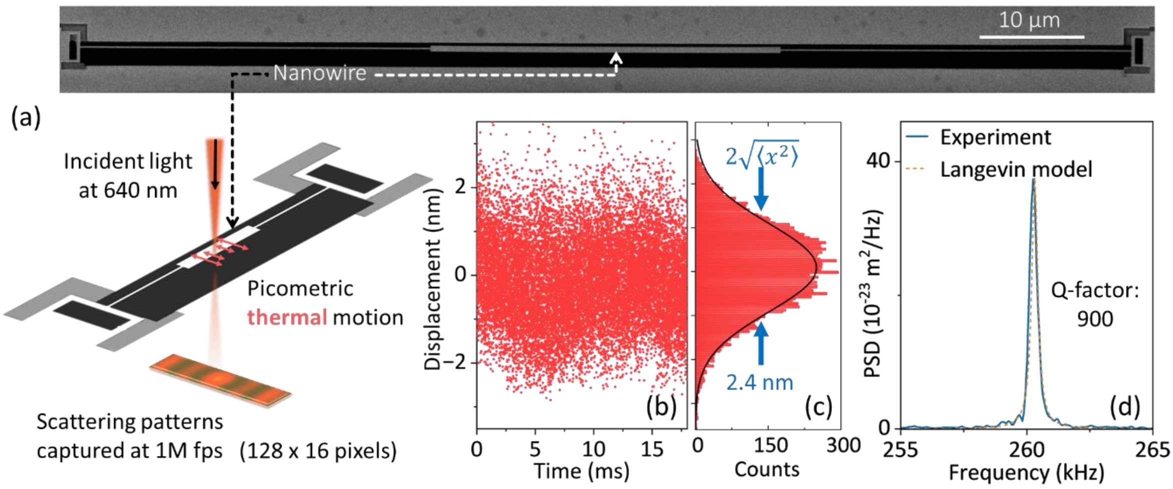

Fig. 1. High-speed optical picometrology resolving microwire thermal motion. (a) Schematic of the experimental configuration for collection of transmission scattering patterns and (above) a scanning electron microscope image the gold-coated silicon nitride microwire. (b) Time series of microwire thermal motion displacement about its equilibrium position retrieved via deep learning-enabled analysis of the scattering patterns. (c) Displacement amplitude histogram overlaid with a Gaussian fit. (d) Power spectral density of displacement, overlaid with a fitting derived from the Langevin model.

These data reveal the expected Gaussian distribution of displacement amplitudes, with a root mean square value of $\langle x\rangle$ = 1.2 nm in the present case (Fig. 1c). They also provide direct measurements (Fig. 1d) of the microwire's fundamental in-plane flexural mode frequency (260.3 kHz) and mechanical quality factor (~900). A fitting of the Langevin model for thermomechanical fluctuation of a harmonic oscillator shows that the ballistic regime of thermal motion – characterized by constant velocity over the observation interval, is to be found at intervals below ~10^{-7} seconds, in the present case.

As a non-contact technique, high frame-rate optical picometrology opens a path to the study of driven oscillatory/transient and thermal (i.e. randomly fluctuational) motion dynamics, and the action of forces (optical, van der Waals, electromagnetic, gravitational, etc.) in micro/nanosystems.