



Ultrafast Hyperspectral Nanomotion Imaging of Ballistic and Brownian Motion in Metamaterial Nanostructures

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Abstract – The building blocks of nanomechanical photonic metamaterials are perturbed by collisions with atoms of ambient atmospheric gas and by phonons in the crystal lattice of the constituent materials. Between collisions movements are ballistic, becoming diffusive (Brownian) at longer time scales. We show how one may distinguish between these regimes using ultrafast hyperspectral SEM nanomotion imaging and discuss their manifestation in the time-dependent optical properties of the metasurfaces.

I. INTRODUCTION

The instantaneous velocity of a Brownian particle was once considered, by Einstein no less [1], to be unmeasurable in consequence of the ultrashort timescale on which it changes. While these timescales are now accessible, mechanical dynamics at the nanoscale, where vibrations can become strongly coupled and highly nonlinear [2-3], remain underexplored because there are no routinely available technologies for quantitative spatial mapping of fast nano/picoscale motion. Here we report a nanomotion imaging technique, implemented on the platform of a standard scanning electron microscope (SEM), with which it is possible to visualize the MHz-GHz frequency thermal (Brownian) and driven harmonic oscillatory movements that underpin the functionality of nanomechanical photonic metamaterials. The technique possesses both high spatial and temporal resolution, providing capability to study the thermodynamics of metamaterial nanostructures at a timescales down to the ballistic motion regime.

II. HYPERSPECTRAL NANOMOTION MICROSCOPY

In conventional SEM imaging, a focused electron beam is scanned over an object and the secondary electron current I(r) is detected and used to generate a static image of the object (r being the coordinate in the object plane). We record real-time nanomotion trajectories by detecting the time dependence I(t,r) of the scattered secondary electron flux (Fig.1a) at every pixel. In this regime, thermal or small driven displacements of the object $\delta r(t)$ result in real-time secondary electron current changes that are proportional to the gradient of the static image of the object in the displacement direction: $\delta I(t,r) \propto (\nabla I(r) \cdot \delta r(t))$.

Frequency domain analysis of this signal reveals natural resonant frequencies and directionally-resolved mean square displacement amplitudes of an object in the diffusive regime; Instantaneous Brownian motion detection relies upon a statistical analysis of recorded positional trajectories. By way of example, Figure 1b shows thermomechanical displacement amplitude spectra for a set of six metasurface beams with different lengths at room temperature thermal equilibrium. Their fundamental in-plane resonance frequencies (between 1 and ~2 MHz) are clearly resolved, with noise-equivalent displacement sensitivity reaching 1 pm/Hz^{1/2}. Figure 1c shows the measured mean square displacement (MSD) of a single high-Q silicon cantilever moving in its fundamental inplane oscillations, showing the expected quadratic dependence on time at short (nano- to sub-microsecond) scales, characteristic of the ballistic Brownian motion regime where inertia dominates.

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150

200

6

2.2

10-4



Fig. 1. Brownian motion in metamaterial nanostructures. (a) An incident electron beam generates a flux of secondary electrons that is modulated by fast movements of the target object. Spatially and temporally resolved motion sensing is based on frequency-domain analysis of the amplitude and phase of the secondary electron signal. (b) Static SEM image of an array of six free-standing metasurface beams of different lengths [from 30 to 20 µm in 2 µm steps] cut into a 100 nm thick goldcoated silicon nitride membrane their diffusive regime Brownian motion spectra, each presenting a single sharp peak at the length-dependent in-plane resonance frequency. [Coloured dots superimposed on the SEM image denote positions at which the incident electron beam was focused to record the thermal motion spectra.] (c) Measured mean square displacement (MSD) of a silicon microcantilever [12 μ m long × 1.5 μ m thick × 300 nm wide] with inset enlarged detail of short timescale MSD.

1.2

1.4

1.6

Frequency, MHz

2.0

VI. CONCLUSION

In summary, we have developed a dynamic SEM nanomotion imaging technique that can visualize Brownian movements occurring on at nano- to millisecond timescales in the fundamental building block of nanomechanical metamaterials, with sub-Angstrom displacement sensitivity with nanoscale spatial resolution. It can provide for accurate mapping nanoscale oscillatory mode shapes and other dynamic mechanical properties in a wide variety of nano-engineered and naturally-occurring, for example including M/N(O)EMS devices and 2D material structures, while also presenting applications in the exploration of fundamental physics at the frontier of nonequilibrium statistical mechanics.

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