Subatomic Optical Localization and Metrology with Topologically Structured Light

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We report on the first realization of optical pico-motion metrology: The position of a nanowire is localized with 'sub-Brownian' precision better than 100 picometers via deep learning-enabled analysis of topologically structured light scattering from the nanowire.

Despite the tremendous recent progress in super-resolution optical imaging and metrology, a huge gap remains between optical techniques and the atomic scale of resolution accessible in electron microscopy, begging the question, "Are optical measurements on nanostructures exhibiting Brownian motion possible with resolution beyond thermal fluctuations?" Here we report on an experiment in which the average position of a nanowire with a thermal oscillation amplitude of ~150 pm is resolved in single-shot optical measurements with precision of 92 pm using light at a wavelength λ = 488 nm, providing the first example of such sub-Brownian metrology, with ~λ/5,300 precision.

To localize the nanowire, we employ a deep learning analysis of the scattering of topologically structured light, which is highly sensitive to the nanowire's position. We measure the in-plane position of a suspended 17 μm long, 200 nm wide nanowire, cut by focused ion beam milling from a 50 nm thick Si_3N_4 membrane coated with 65 nm gold, relative to a fixed edge of the surrounding membrane (Fig. 1a). This position is controlled electrostatically via the application of a DC bias across the gap. The sample was illuminated with coherent light at 488 nm, with either a plane or superoscillatory wavefront and the intensity pattern of scattered light was imaged in transmission at a distance of ~λ (~0.5 μm) from the membrane. To enable optical measurements of unknown nanowire positions, we created a dataset of single-shot scattering patterns recorded at 301 different positions of the nanowire. 80% of these, selected at random, were used to train a convolutional neural network, i.e. as scattering patterns for known nanowire positions (calibrated *a priori* in an electron microscope). The trained network was then tasked to determine nominally unknown nanowire positions from the unseen 20% of images.

Our results (Fig. 1b, c) show that nanowire displacements can be measured with precision of 92 pm (λ/5,300) with superoscillatory illumination, and 259 pm (λ/1,900) using plane wave illumination. These values should be compared with the 775 pm lattice parameter of the silicon nitride from which the nanowires are manufactured, and the ~220 pm covalent diameter of a silicon atom. With superoscillatory illumination, accurate measurements (with relative error ≤10%) are possible down to 320 pm; For plane wave illumination this threshold is at 816 pm.

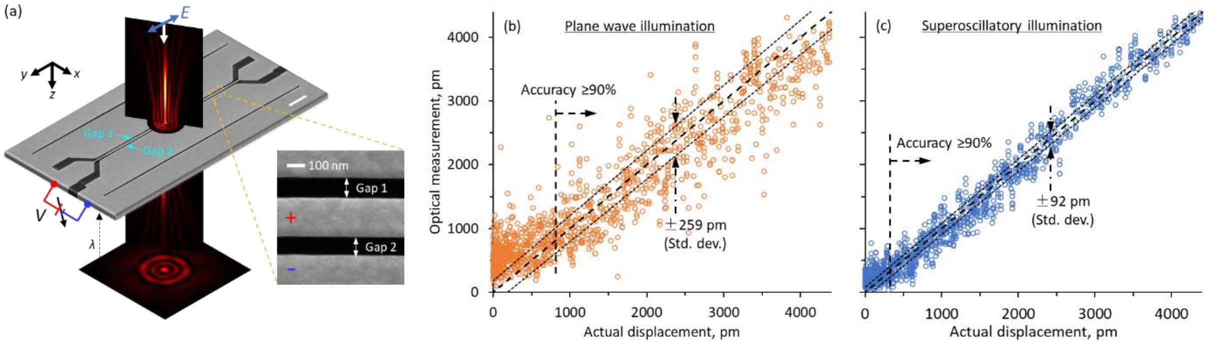

Fig. 1 Measuring nanowire displacement via scattering of topologically structured light. (a) Experimental configuration: Incident light at λ = 488 nm, propagating along *z*, is scattered from the nanowire [enlarged detail shown to the right] and imaged in transmission through a high-NA objective [not shown] focused at a distance λ behind the membrane. (b, c) Optically measured versus actual values of nanowire displacement for (b) plane wave and (c) topologically structured superoscillatory illumination. The statistical spread of datapoints is derived in each case from twenty independent neural network training and testing cycles.

In summary, localization precision surpassing the diffraction limit of conventional microscopes thousands of times over has been demonstrated. The approach can be applied in a range of systems where a regime of controlled positioning is available for training, to then enable non-invasive study of motion induced by ambient forces and fields, or thermal motion. Indeed, there is growing interest in short-range forces and associated phenomena at the nano- to picoscale, which may be investigated using this technique in systems designed to enhance or suppress the mechanism of interest, or where external stimuli (e.g. light) can be selectively applied or withdrawn.