Picophotonics: Sub-Brownian Detection of Nanowire Position with Atomic-scale Resolution using Topologically Structured Light

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Abstract: The first realization of sub-Brownian motion metrology is reported. The position of a nanowire is measured with resolution better than 100 picometers via deep learning analysis of topologically structured light scattering on the nanowire.

Light fields can be structured on deeply sub-wavelength scales – energy hotspots (foci) in superoscillatory light fields can be arbitrarily small, and rapid variations of phase can take place in topologically complex fields at length scales orders of magnitude smaller than the classical diffraction limit. Such fields have important applications potential in

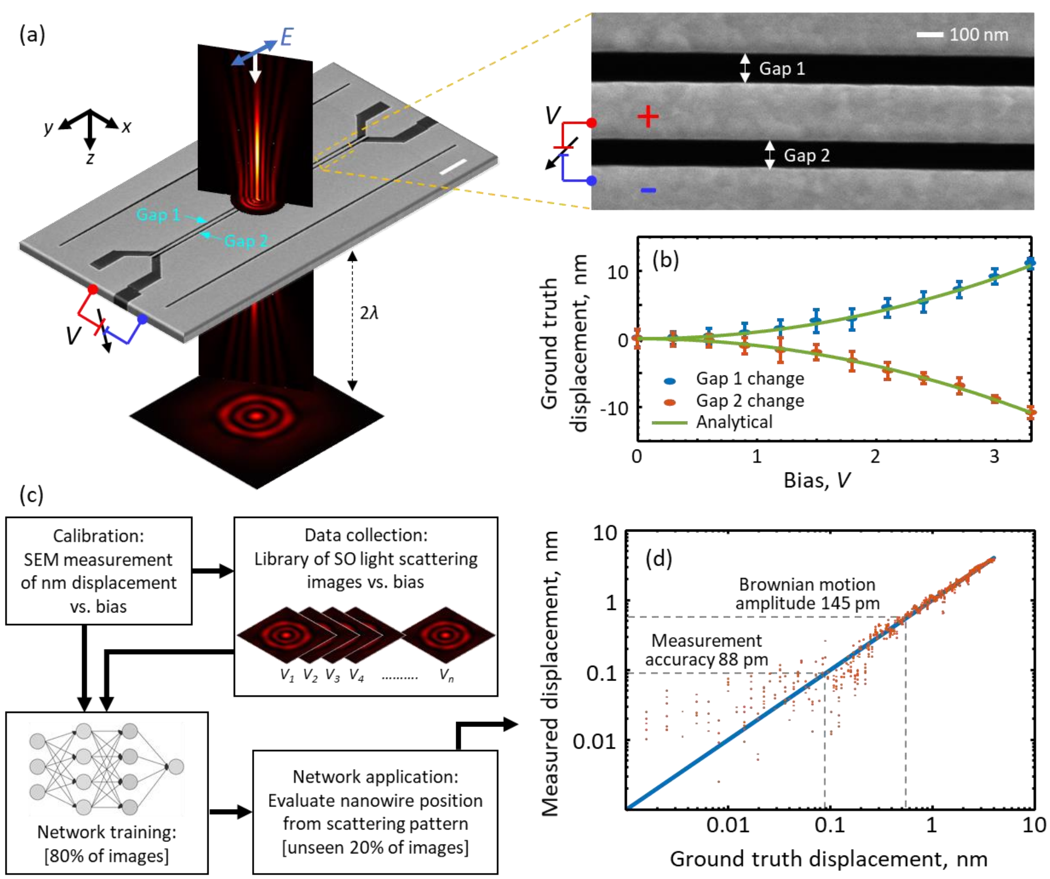

Figure 1. **Measuring atomic-scale nanowire displacements via topologically structured light scattering.** (a) Experimental configuration: Incident topologically structured light is polarized along *y*-direction and propagates along *z* through the free-standing, electrostatically-actuated, Au-coated Si_3N_4 nanowire/slit sample [enlarged detail shown to the right]. (b) Ground truth displacement of the nanowire as a function of applied bias, as determined from SEM imaging. (c) Methodology for deep learning-enabled optical measurements of nanowire displacement. (d) Optically measured displacement of the nanowire [from its equilibrium, zero-bias position] evaluated via deep learning analysis of light scattering, versus ground truth displacement.

the fundamntal science of light and light-matter interactions, as will as in nanoscale metrology, imaging and spectroscopy[1]. In this work, we show that deep learning-enabled analysis of scattering from a superoscillatory light field at the sharp edges of a nano-object can facilitate measurements of object position and displacement at the picoscale. Our approach exploits the changes in far-field scattering/diffraction patterns that take place when deeply subwavelength features of an object overlap with rapid amplitude and phase variations in the incident topologically structured light field. We report here on proof-of-principle experiments in which position of a nanowire is determined with resolution of order 1Å (~1/5000th of the wavelength).

In experiment (Fig. 1a and 1b), we study a subwavelength double slit structure fabricated (by focused ion beam milling) on a 50 nm thick free-standing Si_3N_4 membrane coated with 65 nm gold, wherein the lateral position of the central nanowire (and thereby the widths of the two slits) can be continuously electrostatically controlled. The sample is illuminated, and scattered light is collected in transmission via pair of 100×, NA = 0.9 microscope objectives. The intensity and phase profile of the incident light field, at a wavelength λ = 488 nm (polarized parallel to the slits for the avoidance of exciting surface plasmon polaritons) is controlled by a pair of spatial light modulators. Scattered light is imaged in the far field using a 16-bit camera with an exposure time (~100 ms) much longer than the oscillatory damping time of the central nanowire, at a magnification giving an equivalent pixel size of 12.6 nm.

Using a superoscillatory structured incident light field, we recorded single-shot scattering pattern images for static nanowire displacements from zero to 4 nm (applied DC bias of 0-2V in 10 mV steps). These were analyzed using a convolutional neural network (CNN, containing 3 convolutional layers and 3 fully connected layers): 80% of images (selected at random) for training and validation, the other 20% for testing. For statistical purposes, i.e. to exclude the dependence of measurement outcome on the selection of training images, twenty iterations of the analyses were performed. Figures 1c shows deep learning-derived measurement vs. ground truth values of nanowire displacement from its equilibrium (zero-bias) position. The achieved accuracy of optical displacement measurements is ~88 pm – less than the size of a silicon atom.

It should be noted here that at room temperature, the average amplitude of thermal (Brownian) fluctuations in nanowire position is 145 pm, with a relaxation time of ~500µs. As the integration time of our imaging system is considerably higher (~100 ms), we measure the mean position of the nanowire. As such, our results represent the first example of sub-Brownian motion metrology.

In summary, we have shown experimentally that the relative positions of nanostructures can be measured optically with picometric resolution through the artificial intelligence-enabled analysis of light scattering. Single-shot measurements using topologically structured incident light achieve an accuracy, approaching λ/5000, and considerably beyond (i.e. below) the object's thermal motion amplitude.

[1] N. I. Zheludev and G. Yuan, "Optical superoscillation technologies beyond the diffraction limit", Nature Reviews Physics (2021).