

Single shot optical metrology with resolution beyond $\lambda/10,000$

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Measurement precision in optical localization metrology can be improved manifold by structuring the surroundings of a target to enhance and guide information in a scattered light field to a far-field detector. An experimental positional measurement variance ~ 50 pm ($< \lambda/10^4$) is achieved in single-shot localization of a nanowire under plane wave illumination at $\lambda = 640$ nm.

Recent experiments have demonstrated picometric (atomic scale) accuracy and precision in optical localization measurements based on deep-learning analyses of diffraction patterns of topologically structured (superoscillatory) light scattered from objects. This is made possible by an orders of magnitude increase of Fisher information contained in the scattering patterns when the object interacts with singularities in the incident field, around which there are strong phase and intensity variations over very short length scales. Here, we demonstrate that even greater precision can be achieved using plane wave illumination if the surroundings of the target object are suitably structured. Through an analysis of Fisher information flow ($\neq$ light energy flow), structure in the object plane can be engineered to maximize information reaching a finite far-field photodetector (Fig. 1). Interestingly, the optimal field

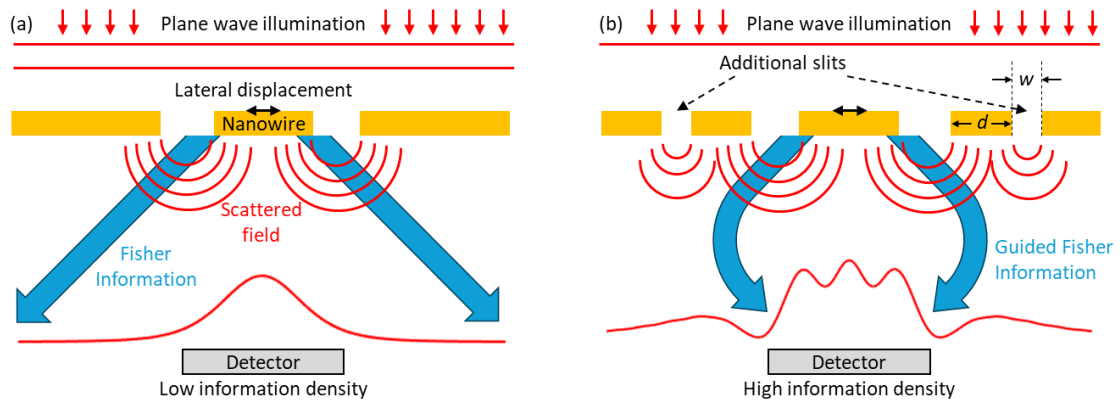


Figure 1: Guiding the flow of information in optical pico-metrology. Schematic cross-sectional illustrations of an arrangement for measuring the lateral displacement of a nanowire via transmission scattering patterns under plane wave illumination. Adding structure to the object plane, as shown in case (b), generates a more complex interference pattern in the detector plane. These additional structural features can be optimized (dimensions d and w) to maximize the flow of Fisher information – a measure of how much information an observable random variable (the scattered field intensity) carries about an unknown parameter (the position of the nanowire) – towards a far-field detector, maximizing the precision of parameter retrieval.

profile in the detector plane (i.e. yielding maximum Fisher information) is found to be superoscillatory. In experiments, we consider a 200 nm wide free-standing nanowire within a 400 nm wide gap, fabricated on a gold-coated silicon nitride membrane (Fig. 2a). A neural network is trained to retrieve the lateral position of the nanowire within the slit from single-shot transmission scattering patterns under plane wave illumination at a wavelength of 640 nm. In the first instance, it does so with a measurement variance of ~ 340 pm (blue data points in Fig. 2c). With the addition of three additional slits on either side of the sample (with widths and positions optimized in FDTD simulations), there is a seven-fold improvement in measurement performance, with variance decreasing to just 49 pm.

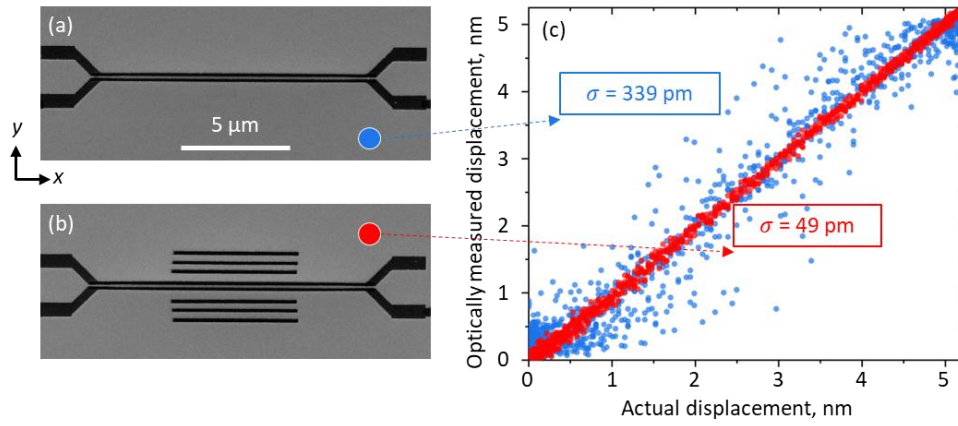


Figure 2. Structural optimisation of nanowire localisation metrology. (a, b) Scanning electron microscope images of gold-coated silicon nitride nanowire samples: (a) nanowire only; (b) nanowire with three parallel slits on either side. Measurements of lateral (y -direction) displacement of the nanowire (controlled electrostatically) are retrieved from transmission scattering patterns under plane wave illumination incident along $-z$ (into the page). (c) Optically measured versus actual values of nanowire displacement.

This work demonstrates that optical measurements yielding picometric precision can be achieved using plane wave illumination and relatively simple (albeit object-specific) structuring of the object surrounding, i.e. without the need to generate complex incident light fields requiring precise, micro/nanoscale alignment with the object. It shows that the optimization of information (as opposed to power) flow according to the target object, measurement task, and detector size/position can provide considerable enhancements in sensitivity.