Controlling Fisher Information Flow in Sub-atomic Precision Optical Metrology

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We show that measurement precision in light scattering metrology can be enhanced manifold by controlling the flow of Fisher Information near a target object via the design of its environment. In experimental nanowire localization measurements at $\lambda = 640$ nm, we achieve ~61 pm ($<\lambda/10{,}000$) precision using this approach.

Recent works have demonstrated picometric (i.e. atomic scale) dimensional and positional precision in optical measurements based on deep-learning analyses of diffraction patterns, through the use of superoscillatory (topologically structured) illumination – leveraging an orders-of-magnitude increase in the Fisher information content of scattering patterns arising from the interaction of an object with singularities in the incident field, around which there are strong phase and intensity variations over very short length scales.

Here, we demonstrate that comparable or even greater precision can be achieved using plane wave illumination *if* the target surroundings are suitably structured. Through an analysis of Fisher information flow (which, importantly, does not coincide with optical power flow), structure in the object plane can be engineered to maximize information reaching the finite aperture of a far-field photodetector.

We consider lateral Δx displacements of a 200 nm wide nanowire centred in a 400 nm wide gap in an opaque screen (Fig. 1a). Measurements precision is enhanced, in this case, by the introduction of additional parallel slits in the screen on either side of the nanowire: interference between light transmitted by these (fixed) slits and the (variable) slits defined by the nanowire itself affect the flow of both energy and information from the object plane to the detection plane, and the dimensions of the additional slits can be optimized to maximize the sensitivity of the light field at the detection aperture to small displacements of the nanowire. Indeed, interestingly, the scattered field ultimately becomes superoscillatory.

In experiment, this approach yields 6.5× better precision than the unstructured-environment reference case – delivering a mean standard deviation of 61 pm through the introduction of just three pairs of slits flanking the nanowire (Fig. 1c).

In summary, this work introduces a simple, efficient, and broadly applicable technique for advancing various forms of optical metrology – illustrating that measurement design tasks can be approached as ‘information engineering’ exercises, analogous to antenna or metasurface design for the enhancement and control of electromagnetic energy flow.

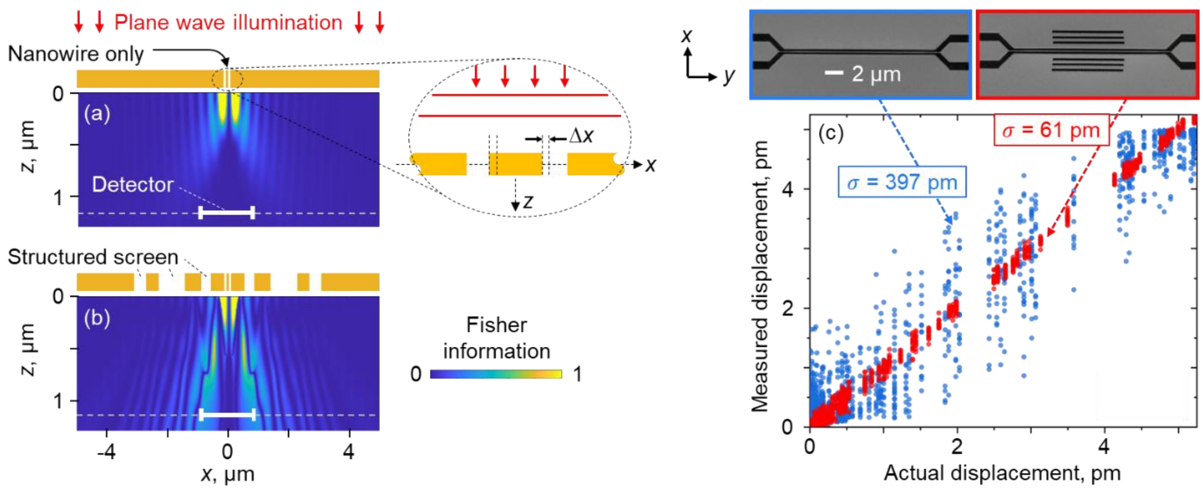

Fig. 1 Optimizing the flow of information in optical localization metrology by structuring the target environment. (a, b) Numerically simulated maps of Fisher information [$FI = (\partial_{\Delta x} I)^2/I$, where I is intensity] associated with $\Delta x = \pm 1$ nm lateral displacements of a nanowire suspended in a gap in: (a) an otherwise opaque screen. Note that almost all FI generated is scattered outside the acceptance angle of the detection aperture, at $z = 2\lambda$ beyond the screen; (b) a screen in which three pairs of additional slits have been opened, with widths and separations [symmetrical about the nanowire] optimized to maximize FI at the detection aperture. (c) Experimental demonstration of optical localization precision enhancement: Optically measured versus actual values of nanowire displacement for a nanowire in isolation [blue dots], and an identical nanowire flanked by three symmetrically positioned pairs of parallel slits [red], as shown in the scanning electron microscope images above. Samples are fabricated on a 50 nm thick silicon nitride membrane coated in 50 nm gold.