META 2025, MALAGA - SPAIN, JULY 22 – 25, 2025

Optical Picometrology

K. F. MacDonald[1], T. A. Grant[1], C.-H. Chi[1], H. Zhou[1], A. Vetlugin[2], E. Plum[1], S. Rotter[3], and N. I. Zheludev[1,4]

[1]Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
[2]Centre for Disruptive Photonic Technologies, TPI, SPMS, Nanyang Technological University, Singapore 637371
[3]Institute for Theoretical Physics, Vienna University of Technology (TU Wien), A-1040 Vienna, Austria
[4]Hagler Institute for Advanced Study, Texas A&M University, College Station, Texas, 77843, USA
[*]corresponding author: kfm@orc.soton.ac.uk

Abstract: The information content of a scattered field increases orders of magnitude with topologically structured (as opposed to unstructured) light, and plasmonic effects can enhance/redirect information flow. On this basis, picometric precision and accuracy can be achieved in optical metrology and imaging.

Complex optical fields can contain structure at deeply subwavelength scales – including point-like singularities, zones of energy back-flow, and strong phase and intensity gradients. The scattering of light from an object can thus depend strongly on exactly where its features are located within such a field. On this basis, precision and accuracy reaching the atomic scale (100-200 pm; $<\lambda/5000$) have recently been demonstrated in single-shot optical measurements of nano-object positions and dimensions, based on deep-learning analyses of their far-field diffraction patterns in topologically structured light (doi: 10.1038/s41563-023-01543-y).

Here, we explain how such performance – reaching far beyond the conventional diffraction limit – is possible, through a Fisher Information analysis of the technique, showing that the scattered field from an object located near a singularity can have information content orders of magnitude higher than the scattered field from a plane wave. We further show how plasmonic effects can resonantly enhance and redirect the flow of Fisher information (very differently from the flow of energy), directly impacting the limits of measurement precision and accuracy; and we illustrate how the concepts can be extended from the constrained problem of retrieving single/few dimensional parameter measurements to the greater challenge of imaging arbitrary nano-objects.