Deeply Sub-wavelength 2D Optical Metrology with Superoscillatory Light

Jin-Kyu So[1], Yu Wang[2], Eng Aik Chan[1], Carolina Rendón-Barraza[1], Benquan Wang[1], Giorgio Adamo[1], Eric Plum[2], Kevin MacDonald[2], Jun-Yu Ou[2], and Nikolay Zheludev[1,2]

1. *Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637371, Singapore*
2. *Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK*

Quantitative optical measurements of deep subwavelength, two-dimensional (2D), nanometric structures with sensitivity to sub-nanometer details address a ubiquitous measurement challenge. The application of artificial neural networks to the inverse scattering problem of one-dimensional (1D) objects such as nano-gaps has led to the retrieval of the structural dimensions with an accuracy far below the diffraction limit of the light illumination. Here, we introduce a single-shot optical metrology approach that resolves two-dimensional features beyond the diffraction limit in a conventional microscope by a neural network processing of scattering patterns. The technique applies to both positive and negative nanostructures, and we compare topologically structured illumination with Gaussian illumination in a transmission configuration. In the case of negative nanostructures (nanoapertures) irradiated with a phase singularity of superoscillatory structured light, our approach achieved an accuracy of λ/52 (9.3nm). For the positive nanostructures illuminated with the Gaussian profile, the accuracy exceeded λ/40.

Topologically structured light fields can contain highly localized intensity hotspots, phase singularities and high gradients of phase at sizes orders of magnitude smaller than the wavelength of light. We introduce a topologically structured superoscillatory light field in a conventional transmission optical microscope. The two-dimensional objects, elliptical nano apertures fabricated on a chromium-coated glass, are placed at the phase singularity of the superoscillatory light fields and the transmission images are collected via an objective lens with NA of 0.9 and a camera (Fig. 1a). From the library of 200 images corresponding to 200 ellipses of different widths and lengths, 80% (selected randomly) are used for training the neural network, 10% for the validation, and 10% for testing (unseen data) – for the retrieval of the dimensions of the ellipses based on a single shot image via the trained networks.

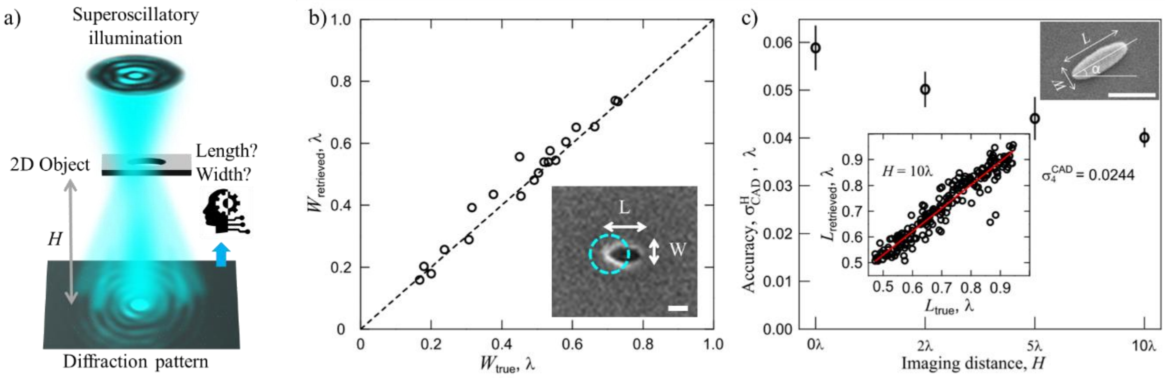

Fig. 1 (a) The experimental schematic of 2D nanometrology with structured light at the wavelength of 488nm or Gaussian illumination at the wavelength of 635 nm. A 2D object is irradiated with a superoscillatory/Gaussian light illumination and its diffraction pattern is recorded at a distance of *H* from the object. After training, the neural network can predict (b) the width information against the ground truth from an unseen scattering image. The scale bar is 250 nm in the inset and the blue circle indicates the phase singularity. (c) Accuracy of the retrieved dimension, *L*, of positive elliptical particles under Gaussian beam illumination at the wavelength of 635nm (FWHM=1.1 λ) at various imaging distances, *H*. (inset) Retrieved values of long-axis of 200 nanoparticles for an imaging distance, *H* = 10 λ. SEM image of a 650 nm-long gold nanoparticle with an ellipticity of 0.33 and 30° of rotation. The scale bar is 500 nm.

To quantify the accuracy of our optical metrology method, we calculate the standard deviation between the retrieved and actual length and width of the testing ellipses. We demonstrate the dimension prediction accuracy of λ/52 (9.3 nm) in a computer experiment and the accuracy of λ/27(18 nm) in the real experiment from a single shot image of various ellipse apertures as shown in Fig. 1b. The dashed line indicates the true size of the elliptical apertures while the circles represent the retrieval size via the pre-trained neural networks. Furthermore, we achieve an accuracy of λ/40 (15.8 nm) in the case of positive ellipses under Gaussian beam illumination but with a 10 times larger dataset (Fig. 1c).

In conclusion, our 2D optical metrology method demonstrates that the size-resolving accuracy can reach λ/52 in a computer experiment and λ/40 in a real experiment for sub-wavelength elliptical apertures and islands. The approach shows great potential for morphological metrology with nanometer resolution using a single-shot image with superoscillatory structured light and the neural network.