

Improving Imaging Resolution with Topologically Structured Light

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In imaging, the information content of a scattered field increases orders of magnitude with topologically structured (as opposed to unstructured) light. On this basis, we demonstrate a multi-fold improvement in binary object imaging resolution.

Precision and accuracy reaching the atomic scale (100-200 pm; $<\lambda/5000$) have recently been demonstrated in optical localization measurements based on deep-learning analyses of nanowire diffraction patterns in topologically structured light (doi: 10.1038/s41563-023-01543-y). This is made possible by the constraining the problem to retrieval of a single dimensional parameter from a known object, and the fact that the information content of diffraction patterns can be orders of magnitude larger when objects are illuminated with superoscillatory light containing phase singularities (i.e. high phase and intensity gradients at deeply subwavelength scale), as opposed to a plane wave. Here, we show that this advantage can be extended to the greater challenge of imaging arbitrary nano-objects: From single-shot diffraction patterns under superoscillatory illumination, a trained neural network resolves feature sizes down to $\sim\lambda/7$ in the profiles of random one-dimensional gratings – a factor of $1.6\times$ smaller than is achieved with plane wave illumination. This advantage is extended to a factor of $2.75\times$ in few-shot superoscillatory imaging, whereby feature sizes down to $\sim\lambda/12$ are resolved.

As target objects, we consider a set of 4096 randomly-generated 10 μm -long gratings with 10 nm pixelation, comprising transparent slits (of arbitrary number, size and spacing) in an otherwise opaque, absorbing screen, illuminated with a monochromatic superoscillatory light field at a wavelength $\lambda = 488 \text{ nm}$ (Fig. 1a). Transmission scattering patterns are calculated, using the angular spectrum method, in a detection plane at a distance of 2λ . Half of the scattering patterns (selected at random) are used to train and validate a convolutional neural network for the task of retrieving the dimensional profile of the central 1 μm -long section of the gratings. The other 2048 scattering patterns are then used for testing, i.e. as unseen patterns for nominally unknown grating profiles. For comparison, the exercise is repeated for plane wave (i.e. unstructured) illumination.

Figure 1b shows representative examples of successful and unsuccessful feature retrieval. Resolving power is quantified (Fig. 1c) in terms of the mean rate of correct pixel retrieval as a function of feature size. Retrieval is all but perfect for features above the classical $\sim\lambda/2$ diffraction limit, with both plane wave and superoscillatory illumination. Beyond this, a success rate $\geq 95\%$ is maintained with plane wave illumination down to feature sizes of 110 nm ($\lambda/4.3$), and with superoscillatory illumination down to 70 nm ($\lambda/6.9$).

Greater superoscillatory advantage is gained from the sensitivity of superoscillatory scattering patterns to the mutual positions of object and incident field features (e.g. grating slit edges vs. singularities). Just two additional diffraction patterns (for mutual displacements $\Delta x = \pm 160 \text{ nm}$ between gratings and the incident beam) provide sufficient additional information to extend the 95% success retrieval threshold down to $\lambda/12.2$. (No such enhancement is possible for plane wave illumination because scattering patterns are invariant with object position in that case).

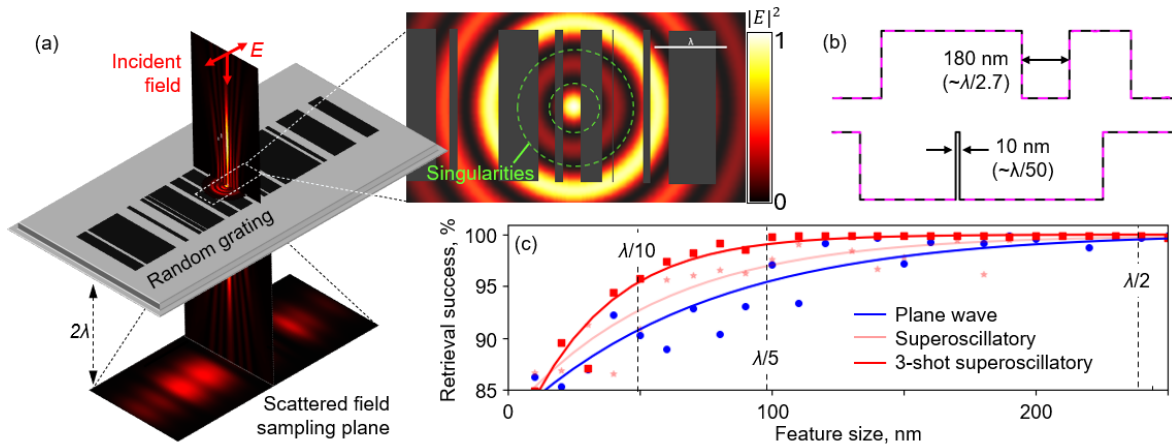


Fig. 1. Imaging arbitrary binary structures using topologically structured light. (a) Gratings are illuminated with a topologically structured (superoscillatory) light field characterized by a central intensity hotspot (of sub-diffraction limit width $\sim 0.3\lambda$) flanked by a series of phase singularities. Grating profile dimensions are retrieved via a deep learning-enabled analysis of transmission scattering patterns. (b) Representative examples of grating profile retrieval with superoscillatory illumination: black lines are the true grating profiles; dashed pink lines are optically retrieved profiles. (c) Mean pixel retrieval success as a function of feature size for single-shot plane wave and single-/few-shot superoscillatory illumination.