Single-shot ptychography & sparsity-based subwavelength ptychography.

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Abstract: We overcome two major limitations in ptychography – a powerful scanning-based coherent diffraction imaging technique. We demonstrate single-shot ptychography, overcoming the scanning-limited temporal resolution and also demonstrate sparsity-based subwavelength ptychography, overcoming the Abbe spatial resolution limit.

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Ptychography is a very powerful coherent diffractive imaging (CDI) technique that has recently gained remarkable momentum in optical microscopy in the visible, extreme ultraviolet and x-ray spectral regions [1]. In ptychography, a complex-valued object is scanned in a step-wise fashion through a localized coherent beam. In each scanning step, the intensity of the diffraction pattern of the object is measured, typically in a Fraunhofer plane. The set of typically hundreds diffraction patterns is used for reconstructing the complex field describing the object. Critically, the illumination spot in each step overlaps substantially with neighboring spot. Ptychography exhibits several advantages over "conventional" CDI techniques, including significant improvement in the robustness to noise, no requirement for prior information (e.g. support) on the object and probe beam, no loss of information due to beam stops, and generally faster and more reliable reconstruction algorithms.

Here we address the two major limitations in ptychography: i) the need for scanning, which poses a major limitation of the data acquisition time, and ii) diffraction-limit spatial resolution. First, we propose and experimentally demonstrate single-shot ptychography, where tens or hundreds of intensity diffraction patterns from array of partially overlapping illuminating spots are recorded in a single exposure. Whereas scanning limits the acquisition time of ptychgraphic microscopes to the range of ~0.1secs, single-shot ptychography allows for ultrafast ptychographic microscopy. Second, we demonstrate numerically sub-wavelength ptychography, utilizing the fact that the sought information (the complex field of the object) can be represented compactly (sparsely) in real space or in a suitable mathematical basis. As an example, we present ~3.5 times resolution enhancement (beyond the Abbe resolution limit) of a biological specimen.

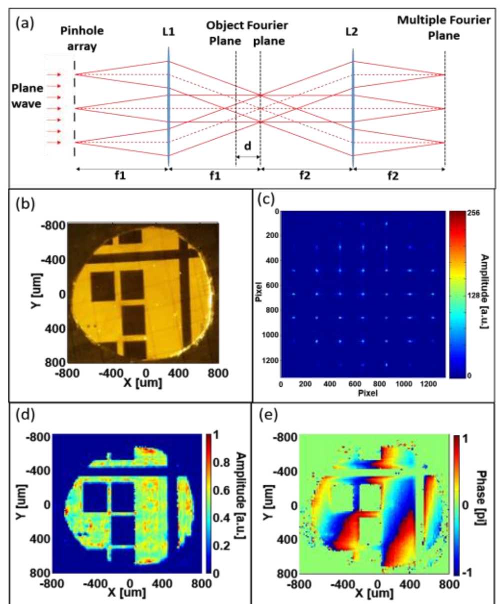

Figure 1: Experimental single-shot ptychography (a) schematic of single-shot ptychographic microscope with ray tracing. (b) Image of the object measured by conventional microscope with x10 magnification. (c) Measured diffraction pattern. Ptychographic reconstruction of the amplitude (d) and phase (e) from the measured diffraction pattern.

In our scheme for single-shot ptychography, a coherent monochromatic plane wave illuminates a square array of N×N pinholes positioned before (or at) the input face of an asymmetric 4f system (Fig. 1a). The pinholes are circular with diameter D and the distance between consecutive pinholes is b. The object is located at distance $d\neq 0$ before (or after) the Fourier plane of the 4f system and the CCD is located at the output plane of the 4f system. As shown in Figs 1a, the object is illuminated simultaneously by multiple (N^2) partially-overlapping beams. Finally, lens L2 transfers the field after the object to k-space domain at the CCD plane (the fact that the object is located distance $d+f_2$ before lens L2 merely adds a phase, which is not detected by the CCD). Thus, the detected intensity pattern in single-shot ptychography consists of clearly distinguished N^2 diffraction patterns in the form of N^2 blocks on the CCD. Moreover, we can associate each block and its diffraction pattern to the diffraction pattern of a beam originating from a specific pinhole and illuminating the object at a specific given spot. Thus, we can employ the reconstruction algorithms of scanning ptychography to single-shot ptychography. Straightforward calculations yield that the cutoff-frequency (which determines the resolution) and field of view of single shot ptychography are approximately $b/2\lambda f_1$ and Nbd/f_1, respectively. Thus, the resolution of single-shot ptychography can get close to the Abbe resolution limit by using f_1~b.

Figure 1 presents experimental single-shot ptychography. A sub-millwatt diode laser (λ=405nm) is spatially filtered and collimated. The spatially coherent light illuminates an N^2=49 square array with b=1.4mm and D=75μm circular pinholes, located at the input plane of a 4f system with $f_1=f_2$=75 mm. The object (shown in Fig. 1b using ordinary microscope) is placed d=18.75mm before the Fourier plane of the 4f system. The measured intensity pattern is displayed in Fig. 1c (exposure time of 180 msec, limited by CCD acquisition time). Figures 1d and 1e show our single-shot ptychographically reconstructed amplitude and phase, respectively, using ePIE algorithm [2]. The smallest features in this image - two opaque 40 microns squares at the bottom left - are clearly observable in the reconstructed image.

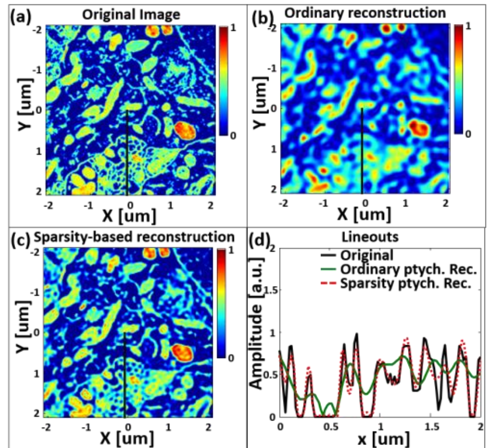

Figure 2: Numerical demonstration of Sparsity-based subwavelength ptychography. (a) Original object (bio-image). (b) Ordinary (diffraction limited) reconstruction. (c) Sparsity-based reconstruction. (d) Line out that corresponds to black vertical line in (a), (b) and (c).

Next, we move to subwavelength ptychography by employing sparsity, i.e. the prior information that the image can be represented compactly in a known physical or mathematical basis. Using sparsity as a "prior" is very powerful because, on one hand it is general (it does not limit the signal to a specific form), and on the other hand it can remove ambiguities. Indeed, we have been employing sparsity in experiments demonstrating sub-wavelength coherent diffraction imaging of relatively simple objects [3,4]. Implementation of the same approach in ptychography can yield sub-wavelength resolution of "real world" objects, including biological specimens and electronic chips, because i) the number of measurements in ptychography is naturally much larger than the number of degrees of freedom of the sought image (which means that it can be represented with large level of sparsity) and ii) ptychography conforms to sparse representation of images in blocks – a feature that is regularly utilized in image compression (e.g. JPEG algorithm). Figure 2 presents a numerical example of ptychographic sub-wavelength imaging. The apparatus is a scanning–based ptychographic microscope using an illuminating circular beam (λ=632nm) with 1μm radius, scanning step of 376nm and detection of 10×10 diffraction patterns with 35 dB SNR in a CDI system with NA=0.9. Figure 2b shows the ordinary (diffraction limited) ptychographic reconstruction using ePIE [2]. Next, we applied our sparsity-based ptychographic reconstruction that searches for the best estimate of the object that is consistent with the set of measurements and is sparse in known mathematical basis. In this example, we assume sparsity in real space. The recovered object is shown in Fig. 2c. Figure 2d shows a lineout of the original image, its diffraction limited image and the sparsity-based reconstruction. Clearly, the sparsity-based reconstruction yields subwavelength resolution. Based on the bandwidths of the reconstructions, we estimate that the sparsity-based reconstruction exhibits 3.5 times higher resolution than the diffraction-limited one.

In conclusion, we addressed two critical limitations of ptychography: the scanning requirement (which sets a hard limit on the temporal acquisition time and therefore the possible temporal resolution) and the Abbe diffraction limit. Our work should lead to subwavelength single-shot ptychographic microscopes that allow retrieving the complex (i.e. amplitude and phase) structure of label-free objects with very high spatial and temporal resolutions.

References

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