Ptychographical imaging of the phase vortices in the X-ray beam formed by nano-focusing lenses.

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Introduction

We present the ptychographical reconstruction of the x-ray beam formed by nano-focusing lenses (NFLs) containing a number of phase singularities (vortices) in the vicinity of the focal plane [1]. As a test object Siemens star pattern was used with the nest features of 50 nm for ptychographical measurements. The extended ptychographical iterative engine (ePIE) [2] algorithm was applied to retrieve both complex illumination and object functions from the set of diffraction patterns. The reconstruction revealed the focus size of 91.4±1.1 nm in horizontal and 70±0.3 nm in vertical direction at full width at half maximum (FWHM). The complex probe function was propagated along the optical axis of the beam revealing the evolution of the phase singularities.

Phase vortices

Phase singularities are a common feature of different forms of waves and represent a fundamental topology property of wave fields. When three or more waves interfere, points of zero intensity could appear. At these positions the phase is undefined (singular), and, in general, all phase values in the interval [0; 2π] occur around a vortex point, leading to a circulation of the optical energy. Vortices can be characterized by the integer number S (positive or negative) that is called a strength or topological charge of the singularity and is determined by $S = (1/2\pi)\oint d\varphi$, where integration is performed over any closed path around the vortex point. Dynamics of the vortices include processes of nucleation, annihilation, and propagation in three dimensions. The lines that are formed by moving of the vortices are called nodal lines (see Fig. 1).

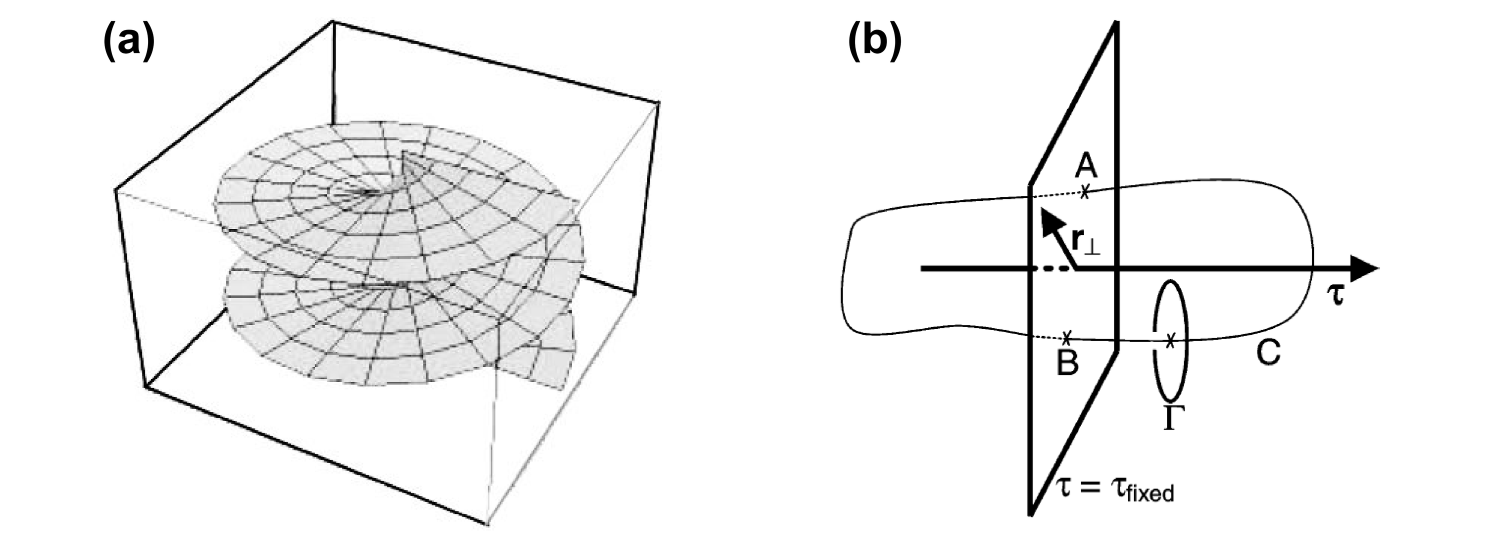

Figure 1. (a) Behaviour of the phase about the vortex core for a singularity with topological charge S=1. (b) Loop formed by vortex cores. The loop intersects the image plane at two points only, yielding a pair of counter-propagating vortices [3].

Ptychographical experiment

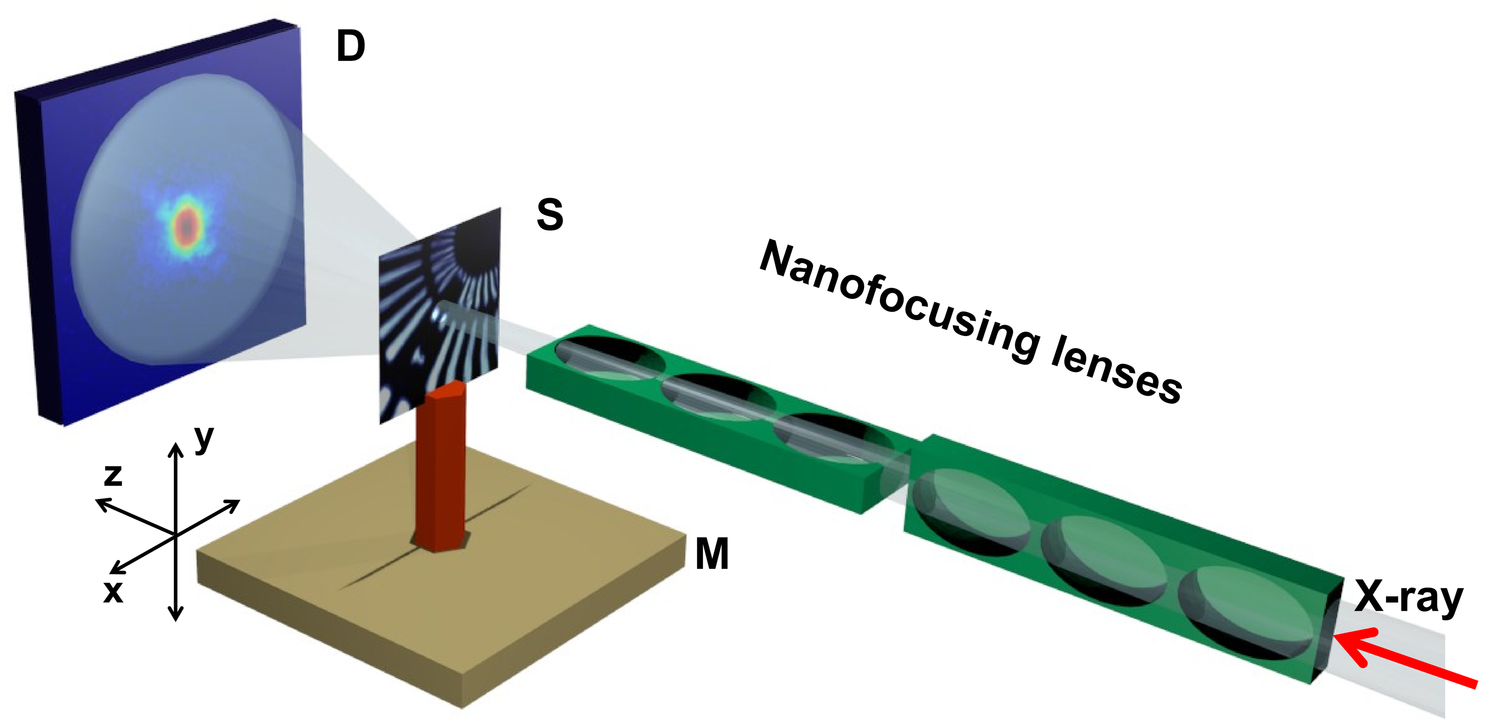

Figure 2. Experimental setup. The incoming x-ray beam (red arrow) goes along the Z axis and is focused by a pair of perpendicularly positioned NFLs. The test sample (S) in the form of the Siemens star is mounted on the movable stage (M) and is illuminated at the positions of a raster grid. Diffraction patterns are collected by the detector (D) 2.1 m downstream.

Experiment was performed at P06 beamline at PETRAIII, Hamburg, Germany [4]. Two perpendicularly positioned NFLs were used to obtain a nano-sized focus of the incident x-ray beam with 15.25 keV energy. The flux of the beam in the focus was 4×10^7 photons/sec. A Pilatus 300K hybrid-pixel detector (Dectris, Switzerland) with the pixel size of 172×172 μm^2 was used. The ptychographical scan was performed on a Cartesian grid with 50 nm step size and 41×41 scan positions, in the horizontal and vertical directions, perpendicular to the optical axis of the beam.

Reconstruction

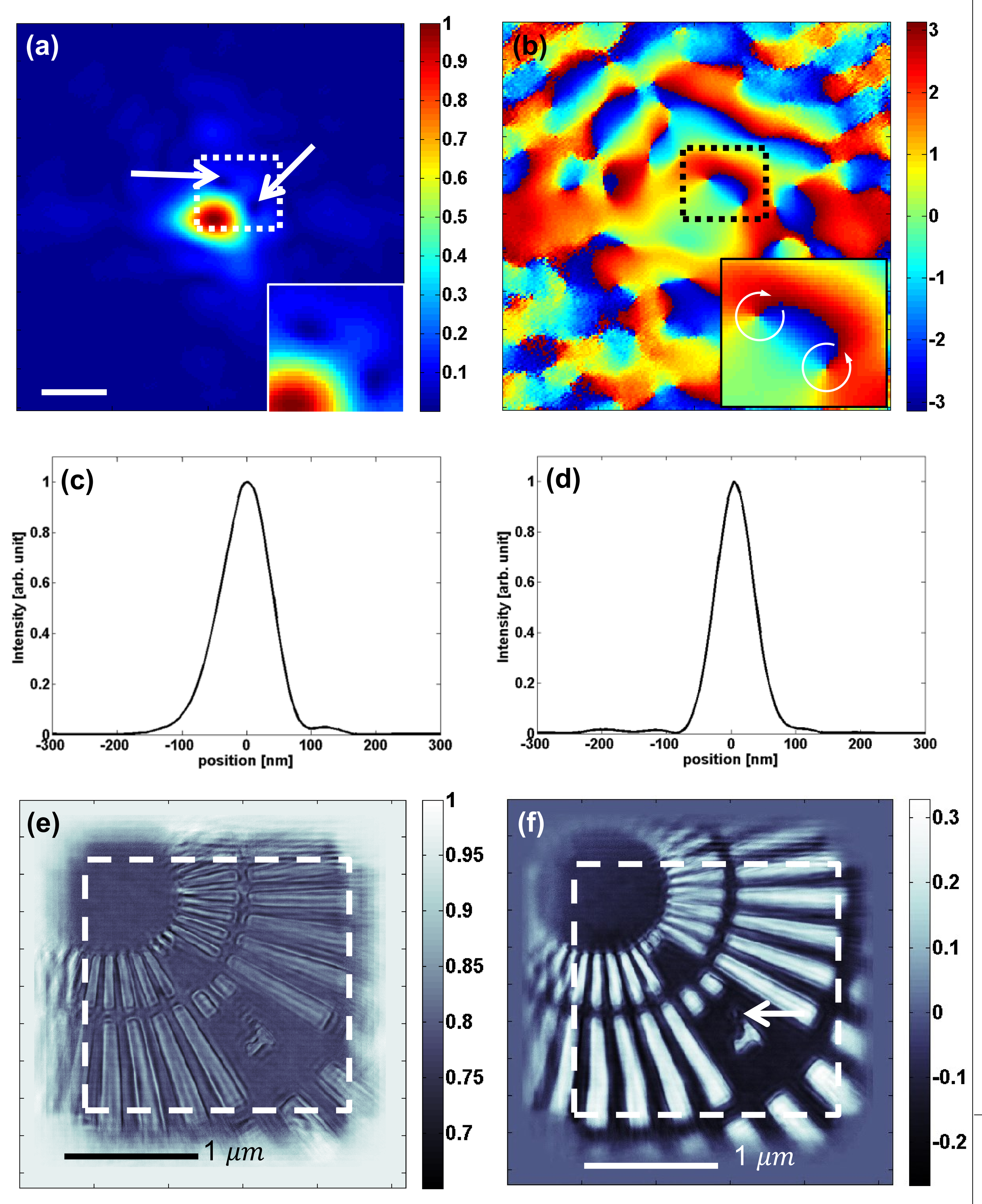

Figure 3. Results of ptychographical reconstruction at the sample plane. (a) Amplitude of the probe function. White arrows indicate two points of zero intensity corresponding to phase singularities (see inset for an enlarged view). (b) Phase of the probe function. In the inset an enlarged view of two singularities with opposite directions is shown. (c) and (d) show horizontal and vertical profiles of the normalized intensity of the reconstructed probe function across the central maximum. (e) Amplitude of the object function. (f) Phase of the object function. Smallest resolved feature is a dot that is 20 nm in diameter. It is shown by an arrow. The color bars in (a) and (e) show normalized values of the amplitude functions and in (b) and (f) values of the phase in radians. Region of the scan is outlined by white dashed lines in (c) and (d). Results are submitted to [1].

Evolution of the vortices

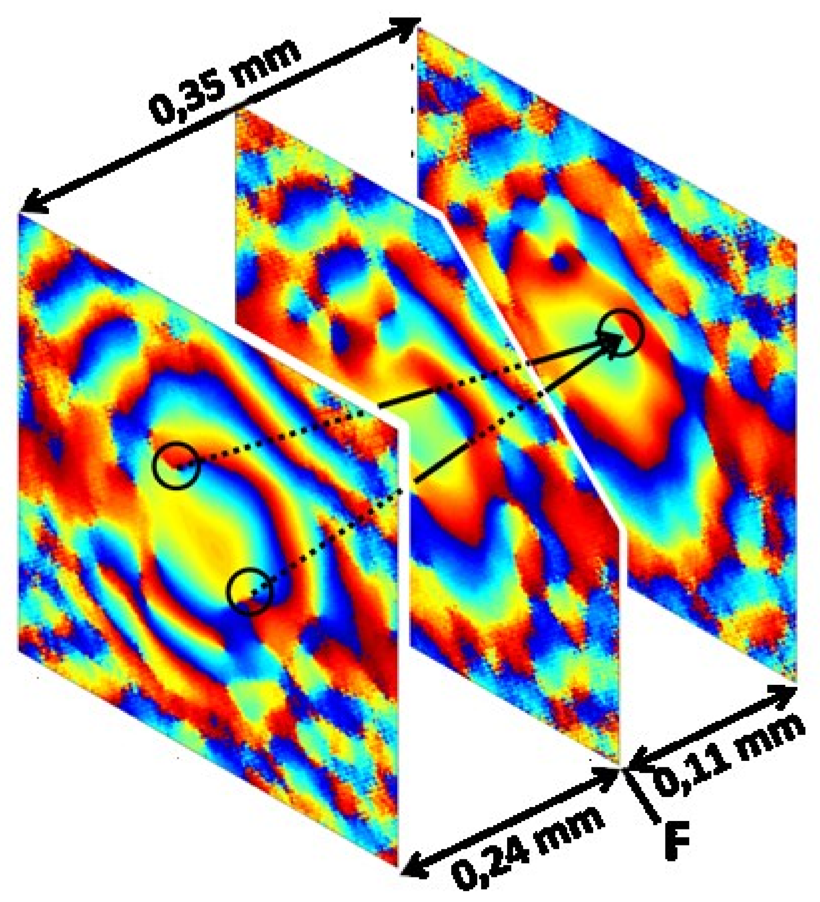

Figure 4. Propagation of the wave field. Three 2D cuts perpendicular to the beam propagation direction are shown: 0.24 mm in front of the focal plane (F), at the focal plane, and 0.11 mm behind the focal plane. At the first position the pair of vortices nucleate, at the last one they annihilate.

An extended ptychographical iterative engine (ePIE) algorithm was applied to determine the complex probe (see Fig. 3 (a, b)) and complex object function (see Fig. 3 (e, f)). They were reconstructed from 1681 diffraction patterns. The field of view was about 2×2 μm^2 and is shown by white dashed line in Fig. 3 (e, f). Reconstruction procedure started from random initial guess of the probe function and a uniform object with a constant transmissivity without a phase shift. The final result was obtained after 100 iterations. The pixel size in this reconstruction is 6 nm. The smallest detail in the object pattern that was resolved is 20 nm in size (see Fig. 2 (c, d)). Distortions in the reconstructed image are due to the drifts of the vertical motors during measurements.

The reconstructed complex wave field profile was propagated from 1 mm in front of the focus to 1 mm behind it in the frame of paraxial approximation. The calculation was performed by using numerical implementation of the Fresnel near field propagation equation.

Conclusions

We obtained the ptychographical reconstruction of the x-ray field focused by NFLs containing a number of phase vortices in the vicinity of the focal plane. After inversion procedure with the ePIE algorithm a complex wave field function was obtained. The pair of vortices closest to the central maximum of the beam with the topological charges ±1 were propagated from nucleation to annihilation plane. The length of the nodal line for these singularities was 0.35 mm in total. Appearance of the vortices in the focal region of the nano-focused beam could possibly affect the quality of the phase retrieval procedure and should betaken into account in future work.

References

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