Observation of an x-ray vortex

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Phase singularities are a ubiquitous feature of waves of all forms and represent a fundamental aspect of wave topology. An optical vortex phase singularity occurs when there is a spiral phase ramp about a point phase singularity. We report an experimental observation of an optical vortex in a field consisting of 9-keV x-ray photons. The vortex is created with an x-ray optical structure that imparts a spiral phase distribution to the incident wave field and is observed by use of diffraction about a wire to create a division-of-wave-front interferometer.

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Phase singularities are a ubiquitous feature of waves of all forms and represent a fundamental aspect of wave topology.[1] An optical vortex phase singularity occurs when there is a spiral phase ramp about a point phase singularity. Alternatively, a vortex can be regarded as a structure in which the energy flows about a loop, forming a circulating eddy—a perspective that can readily be extended to partially coherent waves.[2] From this viewpoint it is clear that vortices should be present even in short-wavelength partially coherent radiation. Here we provide confirmation that complex phase structures, as exemplified by vortices and typically associated with fully coherent light, can indeed be created in the partially coherent radiation from a third-generation synchrotron. We report the experimental observation of a vortex in a field consisting of 9-keV x-ray photons. The vortex is created with an x-ray optical structure that imparts a spiral phase distribution to the incident wave field and is observed by use of diffraction about a wire to create a division-of-wave-front interferometer.[3]

In elementary treatments, the phase of a light field is considered a well-behaved continuous distribution. In recent years it has been realized that the phase distributions for the majority of wave fields almost inevitably contain discontinuities. Indeed, these discontinuities are now seen as a fundamental property of waves.[1] With this realization has come an appreciation for the practical value that such structures might have, and there is now an extensive literature[4] concerned with singular optics.

The optical vortex is a wave field made from photons that carry orbital angular momentum. As a consequence these wave fields are highly stable, particularly when they are coupled with the properties of so-called nondiffracting beams.[5] Moreover, structural stability on propagation also leads to the breakdown of certain approaches to noninterferometric x-ray phase measurement.[6,7] The macroscopic structure of an optical vortex is characterized by the presence of an intensity zero owing to complete destructive interference at the location of the phase singularity. The physical scale of the intensity zero before propagation may be of the order of the wavelength of the radiation,[8] and we therefore note that the formation of a vortex naturally leads to the self-assembly of a small x-ray intensity structure, a possibility that may find use in high-resolution x-ray imaging.

Optical vortices have been produced as a mode of laser cavities,[9] by computer-generated holograms,[10,11] and by use of a spiral phase plate.[12] In the last-named method, which we use here, a plate is manufactured in which the optical thickness ideally increases linearly with azimuthal angle. Varying the optical path lengths through the material of the spiral phase plate imposes a spiral ramp on the phase of the incident wave field.

The x-ray phase plate used in the research described here was manufactured with a mask projection micromachining system (Exitech Series 8000),[13] which used a Lambda Physik LPX210i krypton fluoride excimer laser operating at 248 nm. A conventional chrome-on-quartz mask was used to define the irradiated area and had a lateral resolution of approximately 1 μm. Here it was not possible to create a smooth phase ramp in the polyimide substrate. Accordingly, we used excimer laser ablation, with a series of 15 indexed masks overlaid upon the substrate to produce a 1-mm-diameter spiral staircase structure approximating a spiral ramp. We varied the depths of individual steps by adjusting the laser fluence and (or) the number of pulses used. The result is shown in Fig. 1. In the structures used here the total depth of the spiral was measured with a confocal microscope to be $34.2 \pm 0.5\ \mu$m, corresponding to a phase ramp of $(1.90 \pm 0.03)\pi$ for 9-keV x rays. Note that, because the real part of the refractive index can be written as $n_R = 1 - \delta$, where δ is a small positive number in the x-ray regime, the ramp will induce a phase advance rather than the delay that is familiar from visible optics. For polyimide at 9 keV, as used in the present research, $\delta \cong 3.83 \times 10^{-6}$. Inaccuracies in the overlay procedure coupled with the inherent resolution of the system meant that an approximately

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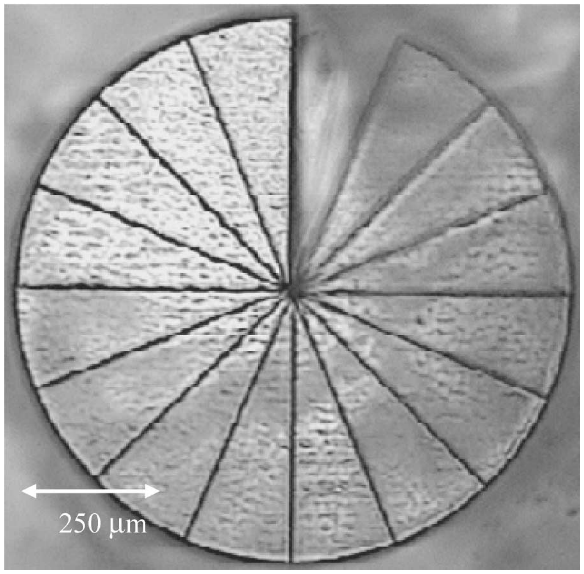

Fig. 1. Optical microscope image, showing a spiral phase plate as manufactured. The image is focused on the deepest step, so the top layer is slightly out of focus.

30-μm-diameter central area of the spiral was poorly defined, as can be seen from Fig. 1. At the x-ray energy of 9 keV used here, transmission through the thickest part of the polyimide spiral is 99%, thus making our spiral staircase essentially a phase-only structure at this energy.

We performed imaging experiments at the Sector 2 Insertion Device Branch Beamline (known as 2-ID-D) at the Advanced Photon Source, Argonne National Laboratory. The undulator source provides a coherent flux [10^{10}–10^{12} (photons/s) 0.1% bandwidth] of x rays in the range 2–32 keV. The beam is defined by a series of slits and mirrors and by a double crystal monochromator ($E/\Delta E = 7000$). Using a procedure reported elsewhere,[14] we measured the horizontal coherence length for the exit slit settings used on the 2-ID-D beam line to be well in excess of 30 μm.[14] The vertical coherence is governed by the effective source size and, for the settings used, was of a length similar to the horizontal coherence length. As this length exceeds the size of the poorly defined region in the center of the spiral, we suspect that the central region will have a minor effect on the generation of the x-ray vortex. The spiral phase plate was placed in air a short distance from the exit window of the beam line. The vortex beam was observed after a propagation distance of 5.8 m through an evacuated flight path by use of an imaging detector that comprised a crystal scintillator magnified through an objective lens onto a CCD camera to produce an effective pixel size of 0.61×0.61 μm. The CCD camera chip contained 1317×1035 pixels. The vortex is expected to show a dark core surrounded by a brighter ring. Figure 2 shows the observed distribution. A bright ring is evident, though not obvious. However, the dark core is clearly observed, as indicated by the inset, which shows the average of a vertical and a horizontal intensity trace through center of the vortex core. The diffraction observed along the edge of the largest physical step in the structure is due not to a phase mismatch but to the machined structure, which has a 7° slope in the wall of each step. In the largest step this slope forms a long enough ramp to produce the observed fringes. In our experimental setup it is difficult to confirm a true zero in intensity. The scintillator crystal and windows, mirrors, and gas in the flight path all contribute to scatter that fills in any intensity zeros in the field.[15] Nonetheless, the dip at the vortex shown in Fig. 2 is consistent with there being an intensity zero at the vortex core.

An intensity distribution of the form shown in Fig. 2 can exist without the presence of a vortex. The signature of a vortex is unambiguously revealed in the phase information. In an interference pattern this signature corresponds to the appearance of a fork in the fringe structure. We therefore chose to use a division-of-wave-front interferometer to determine the phase structure in the wave front. In this case, because of the energetic photons, we simply split the wave field by introducing a 7.5-μm-diameter tungsten wire 3 mm behind the phase plate. To isolate the presence of the vortex, we recorded images both with and without the wire. The result is shown in Fig. 3. The fork in the interference fringes, which is characteristic of a vortex phase discontinuity, is clearly apparent. The inset shows the interferogram obtained when the phase plate has been removed, demonstrating that the fork is not an artifact created by the wire. We also performed a similar set of experiments in which a transparent edge, also acting as a division-of-wave-front interferometer, was scanned across the vortex. As the edge moved farther away from the vortex core, the forked fringe shifted from the first to the second and then to the third fringe, while the fork remained at the same position with respect to the phase plate. Examples of these results are shown in Fig. 4. These observations further confirm the presence of a propagating vortex structure.

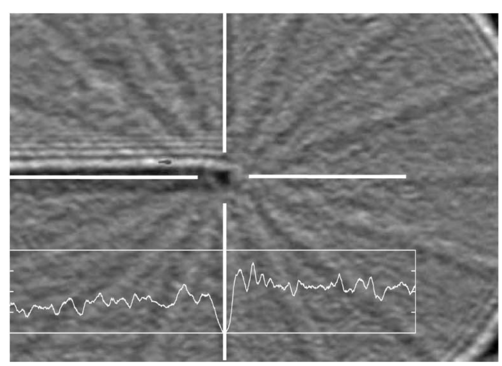

Fig. 2. Image of the x-ray intensity at a propagation distance of 5.8 m from the spiral phase plate. Structure from the nonuniform illuminating field has been removed through division of the original data by the corresponding image with the phase plate removed. The spiral structure can be seen, as can a strong diffraction edge that is due to the slope in the large step joining the top and the bottom of the spiral. A faint ring can be observed about the central dark core region. Inset, average of the horizontal and vertical profiles through the core as shown.

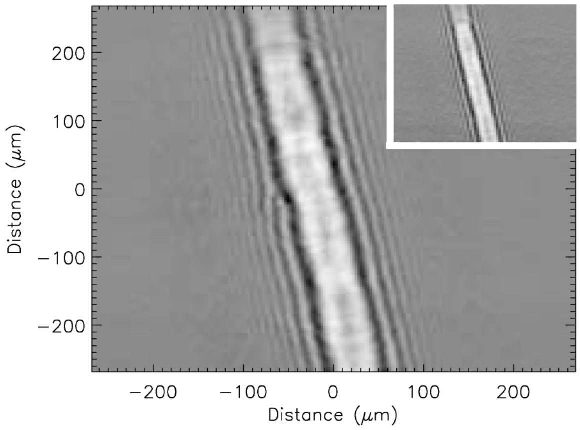

Fig. 3. Fresnel near-field diffraction image produced by the spiral phase plate and a wire, showing interference between the vortex input beam and the diffracted field from the wire. Inset, an otherwise identical image, except that the phase plate has been removed. The standard Fresnel diffraction pattern for a wire is clearly observed.

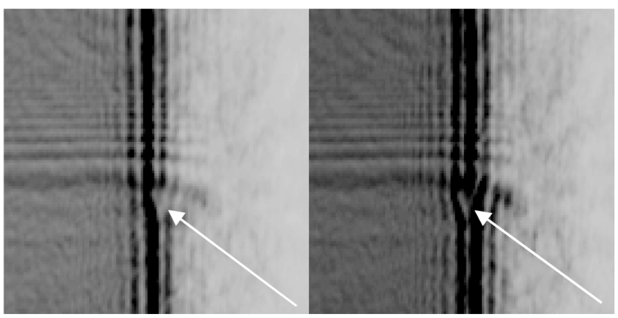

Fig. 4. Two of a sequence of images showing the scan of an edge across a vortex core. The arrows indicating the position of the forked fringe are aligned such that the movement of the edge can be seen, as can the fact that the position of the vortex core (at the fork) remains stationary.

A final confirmation of the desired modification of the x-ray wave field is given by simulation. A Fresnel diffraction simulation that uses the experimental parameters and allows the phase thickness of the phase plate to be a free parameter gives an estimate of the maximum phase shift when it is fitted against the experimental data. The resultant estimate of the maximum phase shift is $(1.8 \pm 0.2)\pi$, in agreement with the value based on measurement of the phase plate's thickness and consistent with the presence of a 2π phase discontinuity.

Our experimental results have confirmed the presence of a propagating 2π x-ray phase vortex structure. The stable topological features of vortex beams should encourage their application to x-ray wave fields and an exploration of their uses in lithography and other forms of x-ray imaging. In particular, we note that collimation of x-ray fields is possible through the introduction of nondiffracting structures, such as Bessel beams containing a phase singularity.[5] We note that the vortex itself might be regarded, in the near field, as a self-assembled optical structure with a characteristic scale equal to the wavelength of the radiation. We therefore envisage that a number of additional imaging modalities should become possible based on this observation. An additional possibility, given the success of high-resolution x-ray imaging observations such as NASA's Chandra X-Ray Observatory, is to use the vortex core as a window to examine a weak x-ray background signal hidden in the glare of a bright coherent source.[16]

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