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Fabrication of X-ray Spiral Masks by Laser Ablation

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ABSTRACT

The manipulation of x-rays by phase structures is becoming more common through devices such as compound refractive lenses, blazed zone-plates and other structures. A spiral phase modulation structure can be used to condition an x-ray beam to produce an x-ray vortex. An x-ray beam in this form can be used as the first step towards a self-collimating beam. Also it can be used as a controllable pathological feature in studies of x-ray phase retrieval.

We describe the microfabrication of a spiral phase modulation structure by excimer laser ablation. A multi-step fabrication using 15 separate chrome-on-quartz mask patterns is used to create a 16 step spiral staircase structure approximating the desired spiral ramp. The results of simulations and initial experimental results are presented.

Keywords: X-ray optics, phase, microfabrication

1. INTRODUCTION

Phase singularities are a ubiquitous feature of waves of all forms and represent a fundamental aspect of wave topology[1]. A screw, or vortex, phase singularity occurs when there is a spiral phase ramp around the point of phase singularity. The intensity distribution consists of a bright annular region surrounding a dark central core. One such field is the TEM^*_{01} field commonly produced as a mode of laser cavities. Visible light phase vortices are of practical importance in the context of optical vortex solitons and the study of vortices has now generated an extensive literature[2]. The phase vortex corresponds to a photon carrying orbital angular momentum and so these structures tend to be highly stable. This stability has known potential in the context of atom optics, where a shaped intensity gradient is used to manipulate a beam of slow neutral atoms[3]. The orbital angular momentum property of the vortex beam has also been used in the rotation of microscopic objects in an "optical spanner"[4]. While extensive, the literature dealing with vorticies appears to be largely restricted to discussions of highly coherent waves such as the optical vortex solitons produced in laser light already mentioned and in amphidromic points in tidal patterns.

It has been shown that using a description of a wavefield in terms of the Poynting vector distribution can be useful in considering effectcs in partially coherent fields[5]. In the context of vorticies the Poynting vector distribution for the wavefield forms a loop, which means that the energy flow can be viewed as a circulating eddy. This picture can also be valid for partially coherent fields. Accordingly, one might expect vortices to appear in the very short wavelength, partially coherent radiation produced at a third generation synchrotron source.

There is a zero of intensity at the location of the phase discontinuity, where there is complete destructive interference, and the scale of this zero is determined by the wavelength of the radiation. We note that, in the context of x-ray optics, the formation of a vortex structure therefore naturally leads to the formation of a very small intensity structure that

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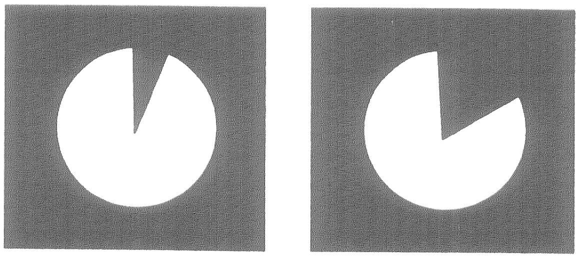
might find application in imaging applications. Vortices are a feature of so-called non-diffracting beams[6]. The ability to produce a self-collimating beam would be a useful feature in the context of x-ray projection lithography. The presence of phase vortices also leads to the breakdown of certain approaches to non-interferometric phase measurement[7,8], which makes their study necessary.

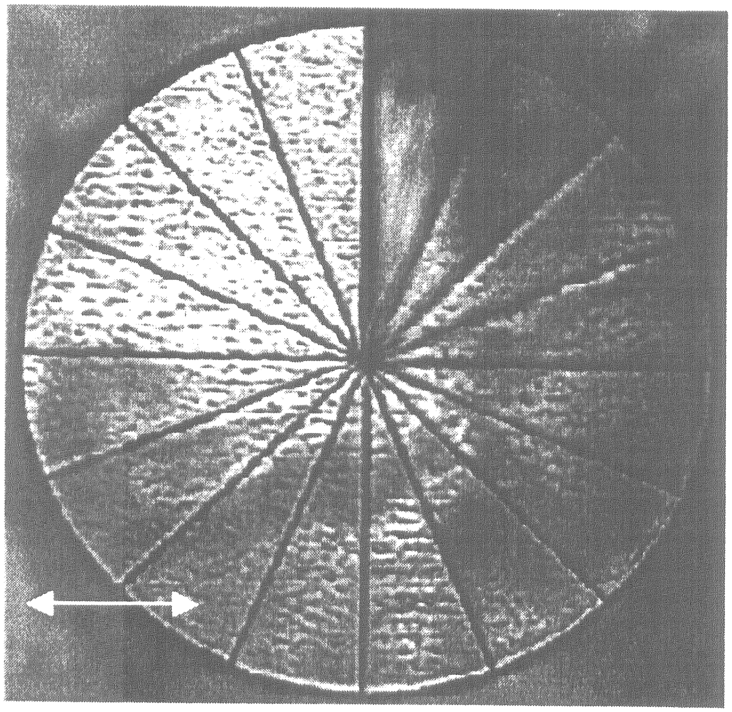
Notwithstanding their potential at x-ray wavelengths, it may have been assumed that the technical issues involved in the controlled creation and detection of a vortex at such short wavelengths were insurmountable. Here we confirm that vortices can be created and detected for x-ray fields by reporting an experimental observation of a phase vortex created with 9keV x-rays.

2. FABRICATION



Optical vortices have been produced as a mode of laser cavities[9], by computer-generated holograms[10,11] and using a spiral phaseplate[12]. In the latter method, the varying optical path lengths through the material of the spiral phaseplate impose the spiral ramp in the phase of the beam. It is this last method that is used here.

The phaseplate was made using excimer laser ablation of a polyimide substrate. Similar structures have been made using laser ablation for visible wavelength phaseplates[13]. The short pulse (20 ns), ultra-violet beam from an excimer laser is an excellent tool for ablative machining of polymers. The laser used was a Lambda Physik LPX210i Krypton Fluoride Excimer laser operating at 248 nm. The beam produced by the laser is about 10 x 200 mm in cross-section and is used as the illumination source for a projection system. The system used was a Mask Projection Micromachining System (Exitech Series 8000)[3]. The projection optics provide uniform illumination of the mask plane with an intensity variation of ±5% rms. The projection lens has a demagnification of 10x, a numerical aperture of 0.3 and a 1.2 mm diameter field. The beam can be attenuated to provide transmission between 5% and 99%, thus providing the ability to adjust the machined depth. The motion of the 4 axis (XYZ and rotation) workpiece holder, and the two axis mask stages are all controlled by the same Computer Numerical Control system, which also drives the beam attenuator and synchronizes the firing of the laser. The workpiece and mask stages are fitted with servo controlled drives and a linear encoder providing 50 nm resolution and ±1 μm accuracy over the full stage travel.



A conventional chrome-on-quartz mask, with a lateral resolution of approximately 1 μm, was used to define the irradiated area. In this work, it was not possible to create a smooth phase ramp in the polyimide substrate. Accordingly, a series of exposures through 15 indexed masks (see Figure 1) were overlaid on the substrate, to produce a 1mm diameter spiral staircase structure approximating a spiral ramp. The depth of individual steps was varied by adjusting the laser fluence and/or the

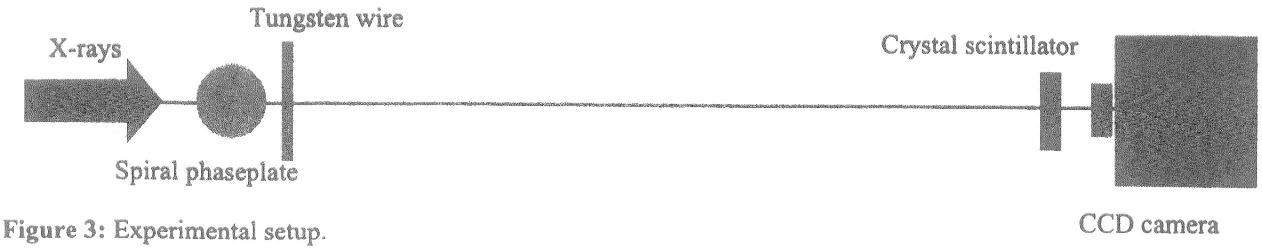


Figure 3: Experimental setup.

number of pulses used. In the structures used here the total depth of the spiral was measured using a confocal microscope to be 34.2 ± 0.5 μm, corresponding to a phase ramp of 95% of 2π for 9 keV x-rays. Inaccuracies in the overlay procedure coupled with the inherent resolution of the system meant that an approximately 30 μm diameter central area of the spiral was poorly defined, as can be seen in Figure 2. 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 a true phase structure at this energy.

3. EXPERIMENT

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 relatively coherent flux (10^{10} – 10^{12} photons/s/0.1% BW) 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/_E = 4000). Using a procedure reported elsewhere[14] the horizontal coherence length of the beam on the 2-ID-D beamline was measured to be well in excess of 30 μm, which was the size of the

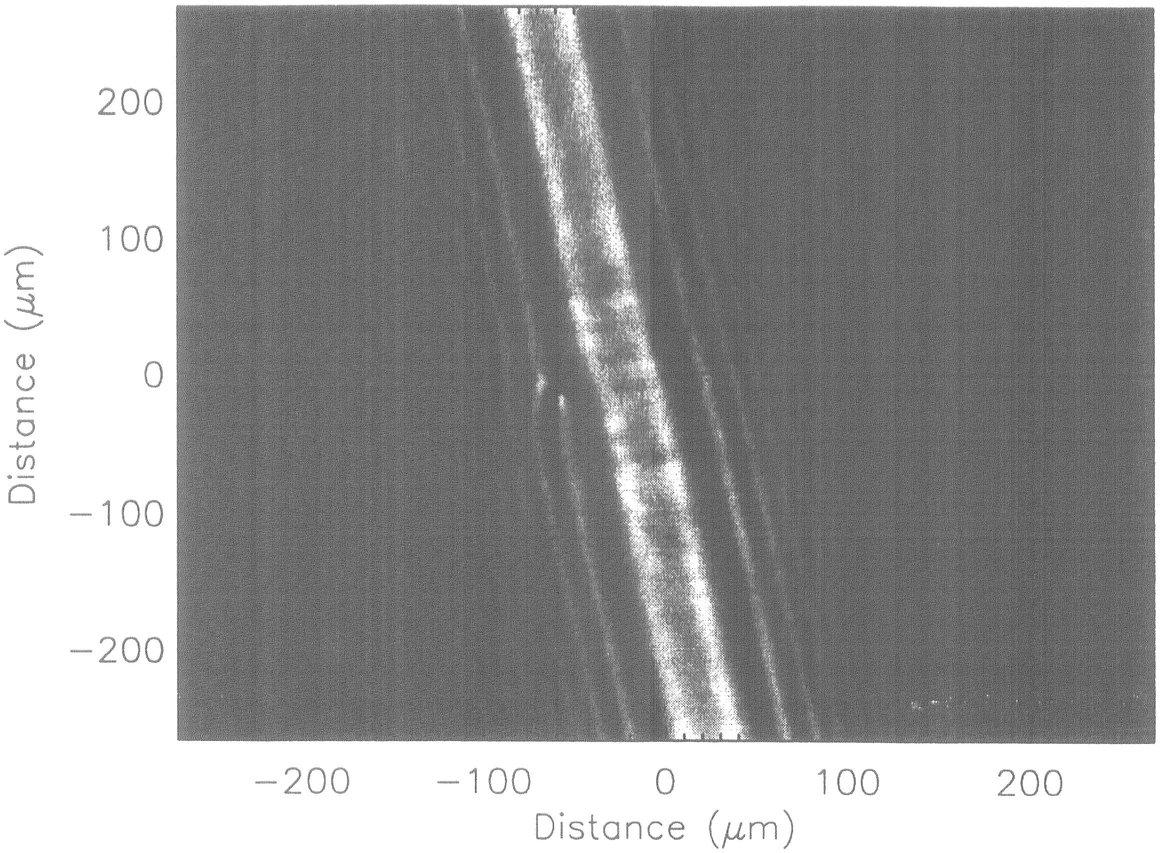


Figure 5: Simulation result for our experimental setup. The image has been thresholded to highlight the similarity in structure to the experimental result.

region in the center of the phaseplate where the approximation to a staircase structure was poor. The spiral phaseplate was placed a short distance from the exit window in air with a 5.8 m propagation distance through an evacuated flight-path to an imaging detector. The detector comprised a doped Yttrium Aluminium Garnet crystal scintillator imaged through an objective lens onto a CCD camera with 1317 x 1035 pixels at a nominal resolution of 0.61 x 0.61 μm.

The appearance of an intensity zero with a surrounding bright ring is often used as an indicator of the presence of a phase vortex. However, the intensity distribution is not conclusive. For an unambiguous detection we must examine the phase information. In an interference pattern this corresponds to the appearance of a fringe splitting into two. Due to the very energetic photons, we therefore chose to use a wavefront-splitting interferometer, in the form of a wire inserted downstream from the phaseplate, to visualize the characteristic fringe pattern of the phase vortex. We introduced a 7.5 μm diameter Tungsten wire 3 mm behind the phaseplate. The experimental arrangement is shown in Figure 3. The resulting image was normalised against an image taken without the wire to remove background structure introduced by imperfections in the beam and from the phaseplate. The result is shown in Figure 4. The fork in the interference fringes, characteristic of a vortex phase discontinuity, is clearly apparent.

4. DISCUSSION

This experiment is easily simulated using elementary Fresnel diffraction of a plane wave incident on the spiral phaseplate and the known properties of the experiment, including the increasing surface roughness of the phaseplate with step depth. A simulation was performed using a 2π maximum phase step in the phaseplate in order to confirm that the forked fringe revealed in this data did indeed conform to the expected structure. The result of the simulation is

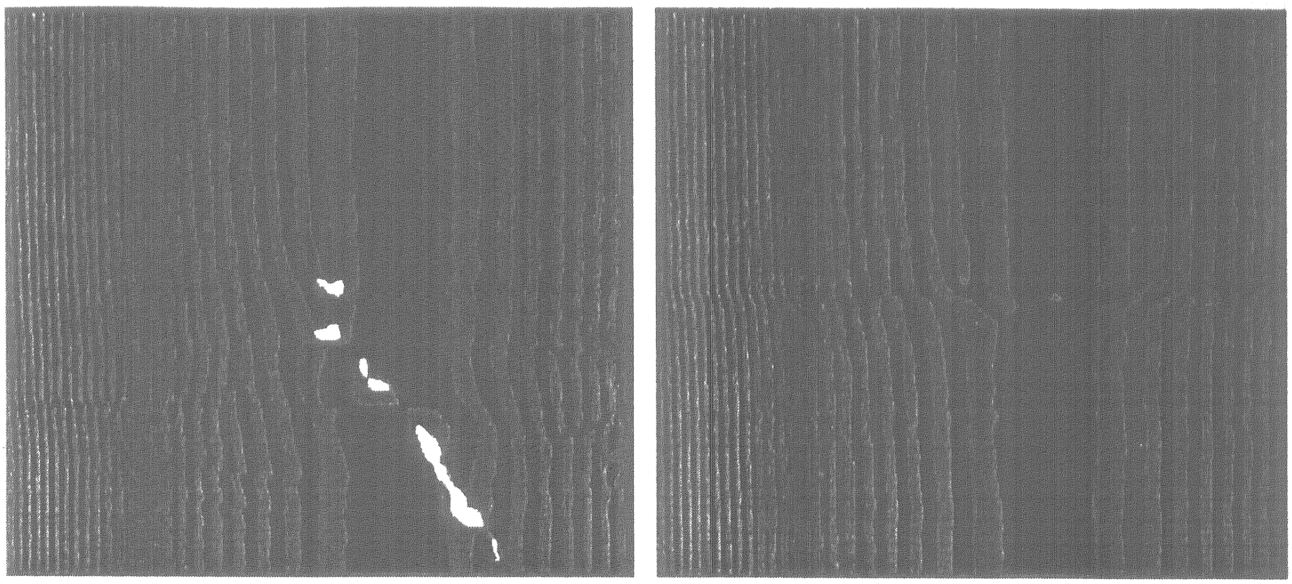


Figure 6: Phaseplate of ~3.5π thickness. The formation of the third fork can be seen. On the left the large phase step in the spiral phaseplate is aligned at 45° to the vertical, on the right at 90°.

shown in Figure 5. It is clear that the agreement is very good, thereby confirming our identification of an x-ray phase vortex beam. The effect of using different thickness phaseplates can also be readily observed using the simulation. As phase thickness is increased from zero to 2π the fringe pattern evolves from the straight-line diffraction pattern produced by the wire alone to the forked pattern shown in Figure 4. The exact evolution depends on the orientation of the phaseplate as for non-2π thicknesses this introduces a linear phase discontinuity at the large phase step in the staircase. Two examples are shown in Figure 6 where the phase discontinuity is aligned at 90° and 45° to the wire respectively. Another feature that can be observed in Figure 6 is an additional fork in the fringe pattern due to the fact that a ~3.5π phase thickness was used in the simulations. In principle it would be possible to minimize the difference between the simulated and experimental images as a function of phase thickness and orientation of the phaseplate thereby obtaining an estimate of the actual thickness if the composition is well known. In practice, experimental uncertainty and uncertainty in the inputs to and the numerical calculations themselves in the simulation are unlikely to allow better than a 10% estimate of the thickness by this method. In our case this approach gives an estimate of the phaseplate thickness with a 10% uncertainty of 33 ± 3 μm, which is in good agreement with the measured value.

5. CONCLUSIONS

The agreement between our simulation and the experimental data shows that the spiral phaseplate does in fact produce an x-ray optical vortex. This result is surprising considering the difficulty that is usually attendant on manufacturing and using x-ray optics. The stable topological features of vortex beams should encourage their application to x-ray wavefields with possibilities in lithography, x-ray imaging and in phase studies. In particular, collimation of x-ray fields is a possibility. Certain beam profiles, including Bessel beams, which have a phase singularity may propagate in a non-diffracting manner in a linear media[6]. We may be able to combine various such beams to produce non-diffracting flux with useful intensity profiles.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Berry, M. V. & Upstill, C. Catastrophe Optics: Morphologies of caustics and their diffraction patterns. *Progress in Optics* **18**, 257-346 (1980).

[2] Rozas, D., Law, C. T. & Swartzlander, Jr, G. A. Propagataion dynamics of optical vortices. *J. Opt. Soc. Am. B* **14**, 3054-3065 (1997) and references therein.

[3] Harvey, E. C. and Rumsby, P. T. Fabrication techniques and their application to produce novel micromachined structures and devices using excimer laser projection. *Proc. SPIE* **3223,** 26-33 (1997).

[4] He, H., Friese, M. E. J., Heckenberg, N. R., and Rubinsztein-Dunlop, H. Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity, *Phys. Rev. Lett.* **75,** 826 (1995)

[5] Paganin, D. and Nugent, K. A. Noninterferometric phase imaging with partially coherent light. *Phys. Rev. Lett.* **80,** 2586 (1998).

[6] Chávez-Cerda, S., McDonald, G. S. & New, G. H. C. Nondiffracting beams: traveling, standing, rotating and spiral waves. *Opt. Comm.* **123,** 225-233 (1996).

[7] Nugent, K. A., Gureyev, T. E., Cookson, D. F., Paganin, D. & Barnea, Z. Quantitative phase imaging using hard x-rays. *Phys. Rev. Lett.* **77,** 2961-2964 (1996).

[8] Allen, L. J., Faulkener, H. M. L., Nugent, K. A., Oxley, M. P. & Paganin, D. Phase retieval from images in the presence of first order vortices. *Phys. Rev. E* **63,** 037602 (2001).

[9] Coullet, P., Gil, L. & Rocca, F. Optical vortices. *Opt. Comm.* **73,** 403-408 (1989).

[10] Bazhenov, V. Yu., Vasnetsov, M. V. & Soskin, M. S. Laser beams with screw dislocations in their wavefronts. *Pis'ma Zh. Eksp. Teor. Fiz.* **52,** 1037-1039 (1990) [*JETP Lett.* **52,** 429-431 (1990)].

[11] Heckenberg, N. R., McDuff, R., Smith, C. P. & White, A. G. Generation of optical phase singularities by computer-generated holograms. *Opt. Lett.* **17,** 221-223 (1992).

[12] Beijersbergen, M. W., Coerwinkel, R. P. C., Kristensen, M. & Woerdman, J. P. Helical-wavefront laser beams produced with a spiral phaseplate. *Opt. Comm.* **112,** 321-327 (1994).

[13] Harvey, E. C., Mackin, T. R., Dempster, B. C. and Scholten, R. E. Micro-opticsl structures for atom lithography studies *Proc SPIE* **3892,** 266-273 (1999).

[14] Paterson, D. et al. Spatial coherence measurement of x-ray undulator radiation. *Opt. Comm.* **195,** 79-84 (2001).