Soft X-Ray Vortex Beam Detected by Inline Holography

We detected a soft X-ray vortex beam by using the inline holography technique [1]. A holographic image is observed as an interference pattern between vortex waves produced from a fork grating and divergent waves from a Fresnel zone plate. By employing spatial frequency filtering, we successfully obtained a spiral phase distribution with a topological charge $\ell = \pm 1$. Our present study may offer a new type of probe for the characterization of topological defects in magnetic textures.

Since the generation of a visible light vortex beam, which has spiral wavefronts, was proposed by Allen *et al.* [2], vortex beams have attracted significant interest in diverse fields, including superresolution microscopy and optical tweezers. In the soft X-ray region, some techniques for generating vortex waves, such as helical undulators [3] and diffractive optics [4], have been reported in recent years. As soft X-rays are widely used to probe magnetic materials owing to their high sensitivity to the spin density of 3*d* and 4*f* orbitals, a soft X-ray vortex beam is expected to be a new type of magnetic probe.

A vortex beam is also known to be generated via a phase defect in a material. It has been reported that a hard X-ray vortex beam is produced by dislocation singularities in a silicon single crystal [5]. Correspondingly, soft X-rays could be converted to a vortex wave via phase defects in a magnetic texture, such as a magnetic Bloch point in skyrmion or helical lattices. These defects, and particularly their dynamics, have attracted much attention because of the possibility of applications in magnetic memory devices. Hence, it is important to characterize their topological properties, such as topological number, which gives the number of times that the magnetic order parameter passes through the interval [0 2π] following a closed loop. It is notable that the topological number of the phase defect can be transcribed to the topological number of the vortex waves. Thus, detecting the soft X-ray vortex beam generated from a phase defect would lead to effective probes for topological properties in magnetic textures. To this end, it is crucial to visualize the spiral wavefront of a soft X-ray vortex beam.

In this study, we employed the inline holography technique to visualize the spiral phase distribution of a soft X-ray vortex beam generated from a fork grating (shown in the inset of Fig. 2 (a)), which is also regarded as containing topological defects. The experimental geometry is illustrated in Fig. 1. Incident X-rays are focused via a Fresnel zone plate (FZP), and the first-order diffraction from the FZP is selected by an order-sorting aperture (OSA) placed at the focal point. A fork grating with topological number $b = 1$ is placed 680 μm away from the focal point, which generates a vortex beam with topological number $\ell = \pm n$ as nth-order Bragg diffraction. The vortex beam interferes with the reference beam transmitted outside the grating, and the interference pattern is observed using a CCD camera.

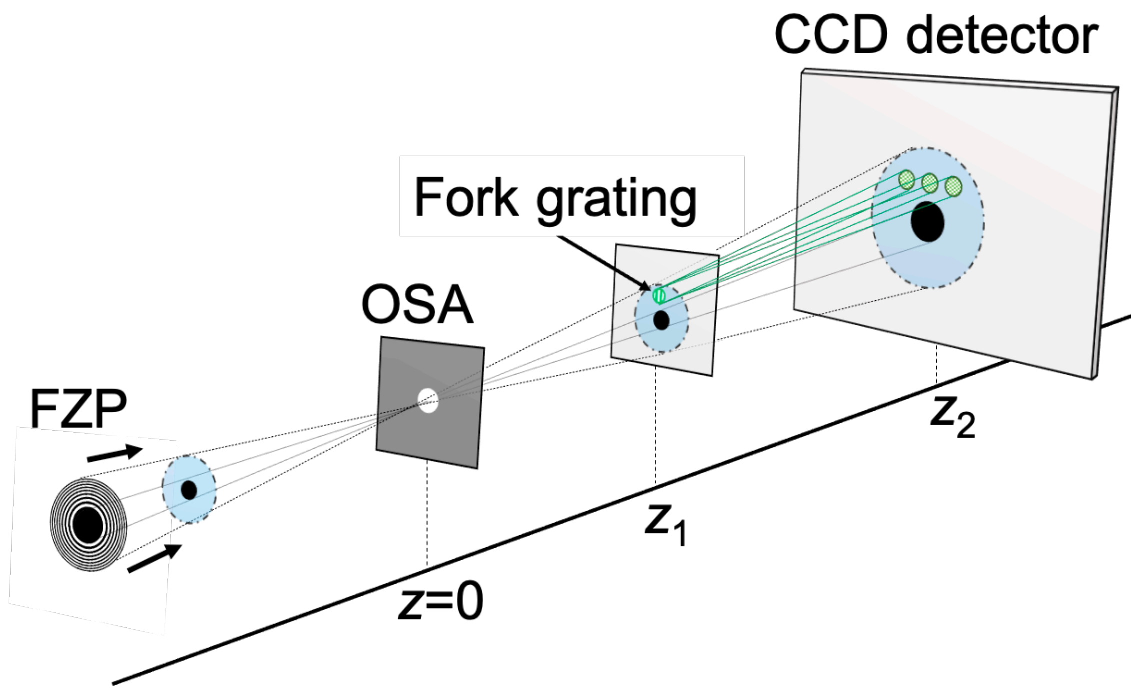

Figure 1: Experimental set-up for inline holography.

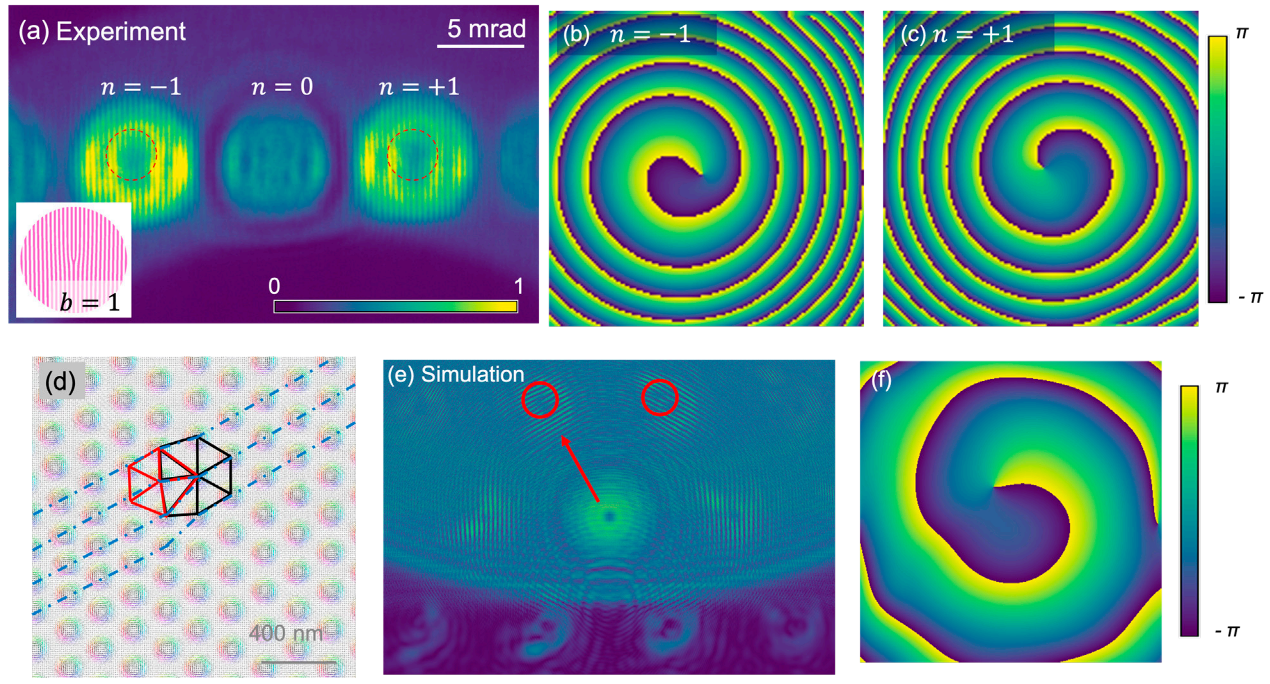

Figure 2: (a) Holographic image of the diffraction waves from the fork grating with topological number $b = 1$ (shown in the inset figure). **(b) (c)** Spiral phase distribution for the Bragg diffraction with $\boldsymbol{n} = \pm \mathbf{1}$. **(d)** Skyrmion lattice with a dislocation and **(e)** calculated holographic image for the Skyrmion lattice. **(f)** Phase distribution of the Bragg diffraction indicated by the red arrow in **(e)**.

Figure 2 (a) shows the interference pattern between first-order Bragg diffraction from a fork grating and the direct reference beam. Intensity modulations along the horizontal direction are clearly visible. In addition, the upper half of the diffraction pattern contains an additional stripe compared with the lower half, and a fork-shaped pattern appears at the center, which implies the formation of a vortex beam. To extract the phase distribution, we employed spatial frequency filtering (details of the method are described in our previous paper [1]). The phase images obtained for the $\ell = \pm n$ diffraction waves (shown in Figs. 2 (b) and (c), respectively) clearly show a spiral phase distribution with $\ell = \pm n = \pm 1$, where the rotation direction is reversed between these vortex waves.

In the next step, we simulated a practical application of the present technique to a dislocation in a magnetic skyrmion lattice (SkL). Magnet skyrmions, which are nanoscale vortex-like spin textures, usually form a hexagonal lattice, while they show arrangements with five and seven neighbors as a dislocation as shown in Fig. 2 (d). Figure 2 (e) shows the calculated holographic image for the diffraction waves from the SkL with a dislocation, where a skyrmion diameter is assumed as 200 nm, obtained by using the scaled fast-Fourier-transform method [6]. The simulated experimental geometry is the same as that shown in Fig. 1. The interference pattern shows a six-fold intensity distribution reflecting the hexagonal symmetry of the SkL, while the diagonal diffractions have a fork-shaped pattern. Using spatial frequency filtering for the diffraction indicated by the red arrows in Fig. 2 (e), we obtained a spiral phase distribution as shown in Fig. 2 (f), which strongly reflects the topological geometry of the phase defects in the SkL. These results clearly indicate that the present technique can effectively characterize the topological properties of magnetic textures.

To summarize, we successfully obtained the spiral phase distribution of a soft X-ray vortex beam generated from a fork grating by using the inline holography technique. The present technique may pave the way to the characterization of topological defects in magnetic textures.

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BEAMLINE

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