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# Development of Multi-scale Soft X-ray Diffraction Microscope for Observing Spin Textures

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We developed a multiscale soft X-ray diffraction microscope for observing spin textures and measured the magnetic domain on a [Pt/Co/Ta] multilayer film. Using this microscope, we obtained nearly real-space images of the magnetic domain without any analysis, in addition to zooming capability.

**KEYWORDS:** Fresnel diffraction, coherent diffraction imaging, magnetic imaging, resonant x-ray scattering

## 1. Introduction

Spin textures, such as magnetic skyrmions, exhibit various fascinating physical properties and have been extensively investigated from the viewpoints of both fundamental science and their applications in next-generation spintronic devices [1]. Resonant X-ray scattering (RXS) is a powerful technique for observing the ordering of electronic degrees of freedom (i.e., charge, orbital, spin, and multipole degrees of freedom) [2, 3]. Moreover, in the soft X-ray region, the RXS signal at the $L_{2,3}$ edge ($2p \rightarrow 3d$ transition) can directly probe the $3d$ electronic state, which is critical to understanding the physical properties in $3d$ transition-metal compounds. Especially, the enhancement of magnetic scattering is enormous at the $L_{2,3}$ edge, and a strong magnetic signal similar to that of magnetic neutron scattering can be observed. For example, Yamasaki et al. detected a magnetic skyrmion crystal in a thin-plate sample ($<$ 200 nm) of FeGe using transmitted small-angle RXS [4]. The results also indicated that the coherence of soft X-ray can be utilized even in Photon Factory, which is an old synchrotron radiation facility operated from 1982 [5]. Hence, we conducted magnetic X-ray imaging studies at the Photon Factory, which led to real-space imaging of the spin texture by coherent diffraction [6–8] and holography [7].

We also investigated the spin texture by scanning transmission X-ray microscopy (STXM) [9], where the sample was placed at the focal point of a Fresnel zone plate (FZP). During this experiment, we investigated the images recorded when the sample was positioned between the focal point and the X-ray detector (Fig. 1). To demonstrate this idea experimentally, we recorded images using a charge-coupled device (CCD) camera temporarily installed in the STXM instrument and obtained a high-quality magnetic domain image without any analysis. After these measurements, we noticed that this kind of microscope was reported as Gabor-type in-line holography [10]. In this microscope, reconstruction is needed to obtain the real-space image because diffraction from the sample is recorded by the CCD camera. However, we noted that the raw data were almost a real-space image [10], consistent with our results. Moreover, the field of view can be freely changed by changing the sample position, although the observable region was limited by the pinhole in our magnetic X-ray imaging

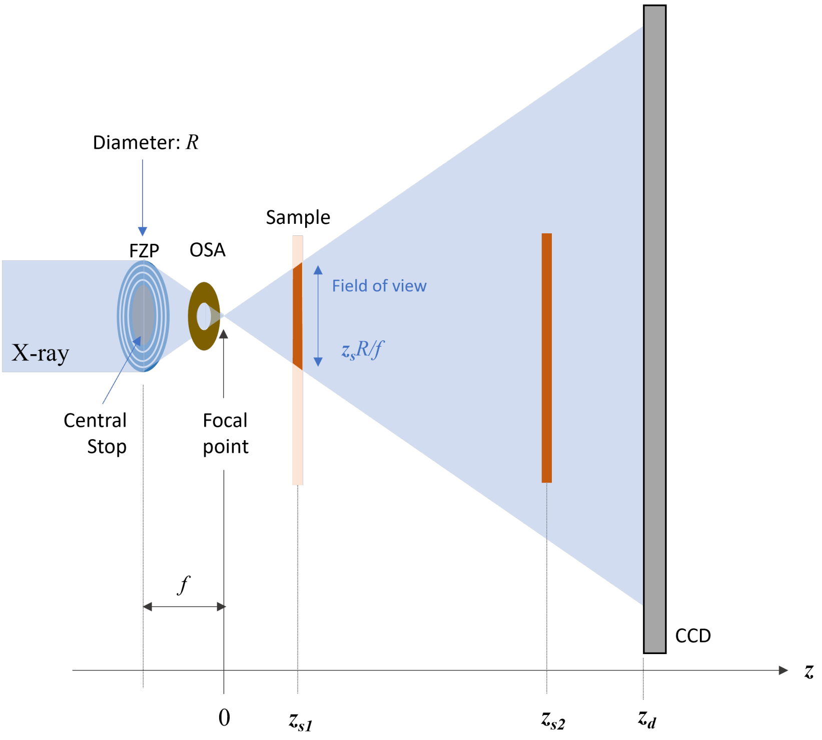

**Fig. 1.** Schematic of the multiscale soft X-ray diffraction microscope with a Fresnel zone plate (FZP), order-sorting aperture (OSA), sample, and CCD camera. The first-order diffraction from the FZP is selected by the OSA. The direct beam is stopped by the central stop on the FZP and the OSA.

studies [6–8]. Zooming ability is an especially important characteristic of this microscope. In addition, high spatial resolution was achieved via reconstruction analysis [11]. Consequently, this technique is suitable for revealing unexpected responses of spin textures under external fields because the important region that needs to be observed for understanding the physical properties is unknown before the measurement. In this report, we present details of the microscope we developed to measure spin textures and demonstrate its zooming ability.

## 2. Experiments

A magnetic multilayer film, [Pt(3 nm)/Co(1 nm)/Ta(2 nm)]$_5$, which is known to be a room-temperature magnetic skyrmion compound [12], was fabricated on a $Si_3N_4$ membrane (thickness: 100 nm) with a capping layer of $SiO_2$ (20 nm) and an underlayer of Ta (5 nm) using a sputter deposition technique. The perpendicular magnetic anisotropy was measured by magnetic susceptibility of the single layer film [Pt(3 nm)/Co(1 nm)/Ta(2 nm)].

The imaging experiment was performed at the APPLE-II type undulator beamline, BL-13A, in the Photon Factory [13]. Right circularly polarized (RCP) and left circularly polarized (LCP) X-rays were used at the Co $L_3$ edge (779 eV) [14]. A schematic of the multiscale soft X-ray diffraction microscope is shown in Fig. 1. The incident X-rays were focused by the FZP (diameter $R$ = 120 $\mu$m; central beam stop diameter 60 $\mu$m). The focal length was $f$ = 1.51 mm at 779 eV, and the focal position was defined as $z = 0$. The diffraction pattern was recorded using an in-vacuum CCD camera (Teledyne Princeton PMI2048, 2048 × 2048 pixels, pixel size 13.5 $\mu$m) installed at $z_d$ = 145 mm from the focal position. The sample was placed between the focal point and the detector. Depending on the sample position, $z_s$, the sample image was magnified by the geometrical factor, $g = z_d/z_s$, although the magnification was limited by the focused beam size near the focal point. Therefore, this microscope is useful for multiscale observation. At $z_{s2}$ shown in Fig. 1, the whole of sample existed within the divergent incident beam from the FZP. Hence, the signals scattered by the sample interfered with the incident beam, corresponding to the reference wave in holography. The size of the field of view, $z_s R/f$, could be changed by varying the sample position, $z_s$. This microscope has been previously reported as the Gabor-type in-line holography, which has been mainly used to observe biological specimens such as cells [10, 15]. The sample shape was properly reconstructed because the edge scattering was detected clearly. On the other hand, the sample was larger than the field of view when the sample was placed at $z_{s1}$. Therefore, only the signals from the sample were measured, and no reference wave was present. This experimental configuration was applied for magnetic domain imaging in the present study.

## 3. Results and discussion

Magnetic domain imaging using the experimental setup detailed in the preceding section has not been previously reported. Hence, we simulated the Fresnel diffraction from a magnetic domain, as shown in Fig. 2. Figure 2(a) is the magnetic domain used for the simulation; only the region irradiated with X-rays is shown. The magnetic domain therefore exhibits a doughnut shape, reflecting the shape of the FZP. The Fresnel diffraction from a magnetic domain was calculated with $z_s = 500$ $\mu$m, as shown in Fig. 2(c). The calculated image is similar to the real-space image of the magnetic domain

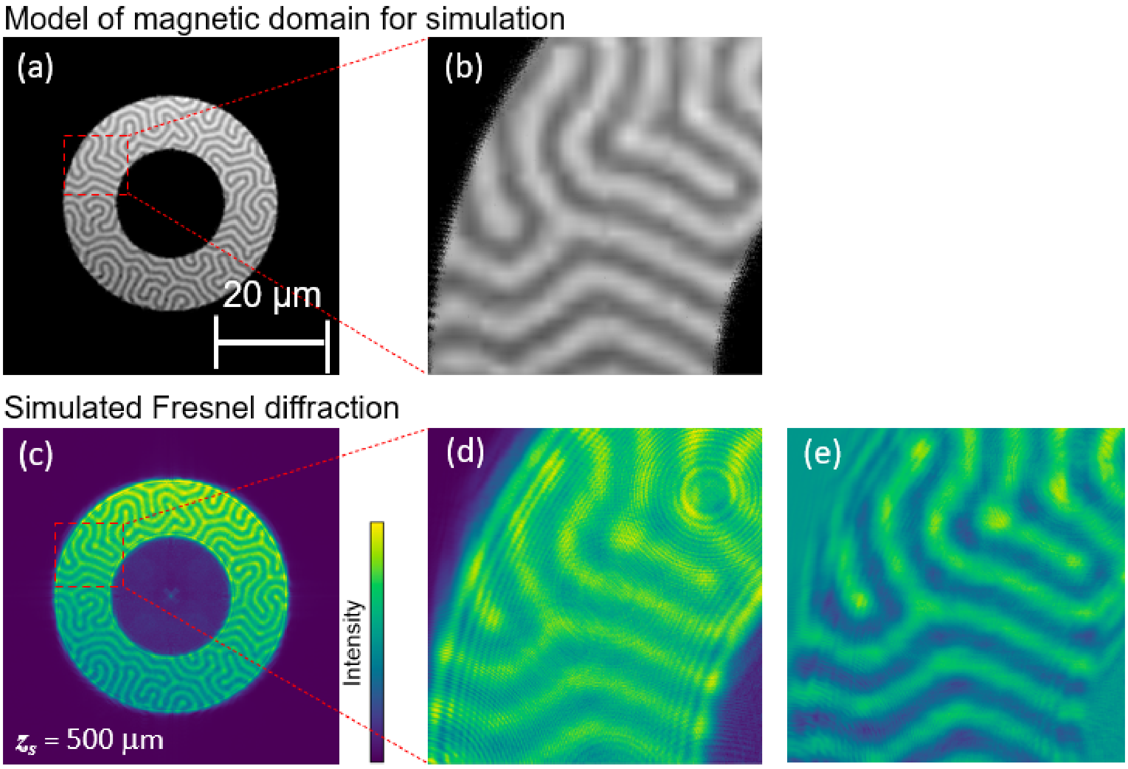

**Fig. 2.** (a) Magnetic domain used for the simulation and (b) the magnified image. (c) Calculated Fresnel diffraction from the magnetic domain and (d) the magnified image. (e) Differential image between Fresnel diffraction patterns calculated for RCP and LCP X-rays.

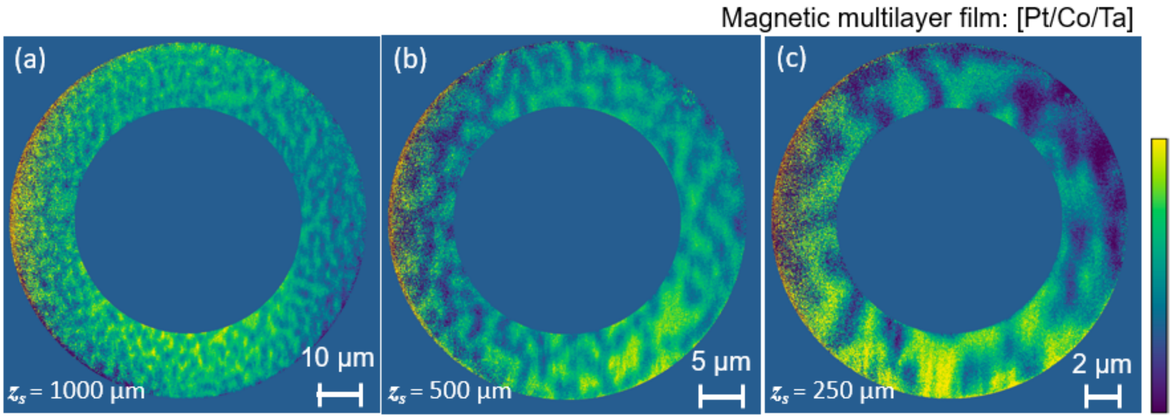

**Fig. 3.** Differential images of Fresnel diffraction from the [Pt/Co/Ta] multilayer film measured at room temperature with the sample positioned at (a) $z_s = 1000\,\mu$m, (b) $z_s = 500\,\mu$m, and (c) $z_s = 250\,\mu$m.

(Fig. 2(a)), although edge scattering and a moiré pattern from the FZP are observed in the magnified image (Fig. 2(d)). Figure 2(e) is the differential image between Fresnel diffraction patterns calculated for RCP and LCP X-rays. The contrast of the magnetic domain is enhanced, and the artifacts from the FZP are reduced.

To test our microscope, we measured the Fresnel diffraction from the magnetic multilayer film at the Co $L_3$ edge (779 eV) [14]. The images were recorded at $z_d = 145$ mm with an exposure time of approximately 10 s [16]. The differential images between RCP and LCP X-rays are shown in Fig. 3. The differential intensity is normalized by the spatial distribution of the incident X-ray intensity. The left region of all the images shows large noise because the incident X-ray intensity was weak in this region. At $z_s = 1000\,\mu$m, the magnetic domain in a wide region is observed. By changing the sample position $z_s$ from 1000 $\mu$m to 250 $\mu$m, we can zoom in on a part of the magnetic domain. The geometrical factor $g$ is 145, 290, and 580 at $z_s = 1000\,\mu$m, 500 $\mu$m, and 250 $\mu$m, respectively. Hence, we demonstrated almost real-space imaging of spin texture, which corresponds to X-ray magnetic circular dichroism (XMCD) imaging. Moreover, the image can be acquired in a single shot, as shown in Fig. 2(c). These results indicate that this technique is more suitable for time-resolved imaging than scanning-type techniques such as STXM.

We have developed a multiscale soft X-ray diffraction microscope for observing spin textures. Using this microscope, we successfully measured nearly real-space images of the magnetic domain on a magnetic multilayer film without any analysis. The zooming ability of this microscope was also demonstrated. In this work, we noted that the real-space image can be recorded without any analysis. Using the reciprocal-space information provided by this microscope, we recently detected a spiral phase distribution of a vortex beam. Moreover, we propose that this technique would be an effective probe for topological defects in spin textures and have indicated its potential to characterize the topological numbers of the defects [17, 18]. These results indicate that our soft X-ray diffraction microscope still has unexplored capabilities to measure spin textures and that the observation technique should be selected depending on the target object. To clarify the capabilities of our soft X-ray diffraction microscope, we are conducting magnetic imaging studies to detect various spin-textures. Finally, we consider that the dynamics and kinetics of spin-textures will become a future important subject in our synchrotron radiation facility [19]; hence, further investigations using our soft X-ray diffraction microscope are strongly desired.

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