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Lorentz Implementation of STEM Holography

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Lorentz TEM (LTEM) is one of few methods capable of imaging magnetic features at the nanoscale. However, the attainable resolution is relatively poor when compared to that of standard high-resolution TEM. The resolution of Lorentz TEM and off-axis electron holography is typically at best 5-10 nm [1, 2]. This limits the possible understanding of magnetic materials. One important example is the skyrmion, which is a donut-shaped magnetic structure. There is interest in using them as low power memory storage and understanding their dynamics is vital. However, they can be as small as 1nm [3]. The best resolution reported for Lorentz microscopy is approximately 1 nm and was achieved by Lorentz STEM (LSTEM) with differential phase contrast (DPC) analysis in an aberration-corrected instrument [4]. STEM Holography (STEMH), a recently developed technique [5–8], can achieve comparable resolution.

In STEMH, we place a nanofabricated diffraction grating in an aperture above the sample to produce multiple diffraction probe beams (Figure 1b). We scan the probes such that the zeroth order passes through vacuum and one side of the diffraction pattern interacts with the sample. At the camera, the diffracted probes are overlapped to form an interference pattern from which the phase shift induced by the sample can be measured [5–8]. Like off-axis electron holography, STEMH measures the amplitude and phase of the sample's transmission function while DPC measures the local phase gradient. However, biprisms, which are typically used to divide the beam in off-axis holography, require a more complicated installation and a much larger coherence width than the diffraction gratings used in STEMH [5–8]. As in LSTEM, the resolution of STEMH is limited only by aberrations, coherence, and the convergence angle of the probe [8]. Therefore, Lorentz STEMH (LSTEMH) should achieve resolution comparable to LSTEM with DPC analysis. Additionally, spherical aberration can be included in the design of the diffraction grating [9, 10], potentially enabling 1 nm resolution in an instrument lacking probe correction.

We simulated Lorentz STEMH of three Bloch skyrmions with a radius of 4 nm in an 80nm thick uniform ferromagnetic thin film (Figure 1). We simulated the magnetization of this specimen (Figure 1a) and calculated the phase shift imparted on an electron beam passing through it (Figure 1b) using the Mansuripur algorithm [11]. From this phase we calculated the magnetic induction of the specimen (Figure 1c). We then simulated LSTEMH of the thin film with a 1 nm probe. To produce a more realistic simulation, we added shot noise to the interference pattern obtained at each scan location. The phase of the thin film measured by STEMH is shown in Figure 1e. From this phase, we then calculated the magnetic induction (Figure 1f). Despite some noise, the structure of the three Bloch skyrmions is readily apparent and agrees well with the magnetic induction calculated directly from the simulated specimen (Figure 1c).

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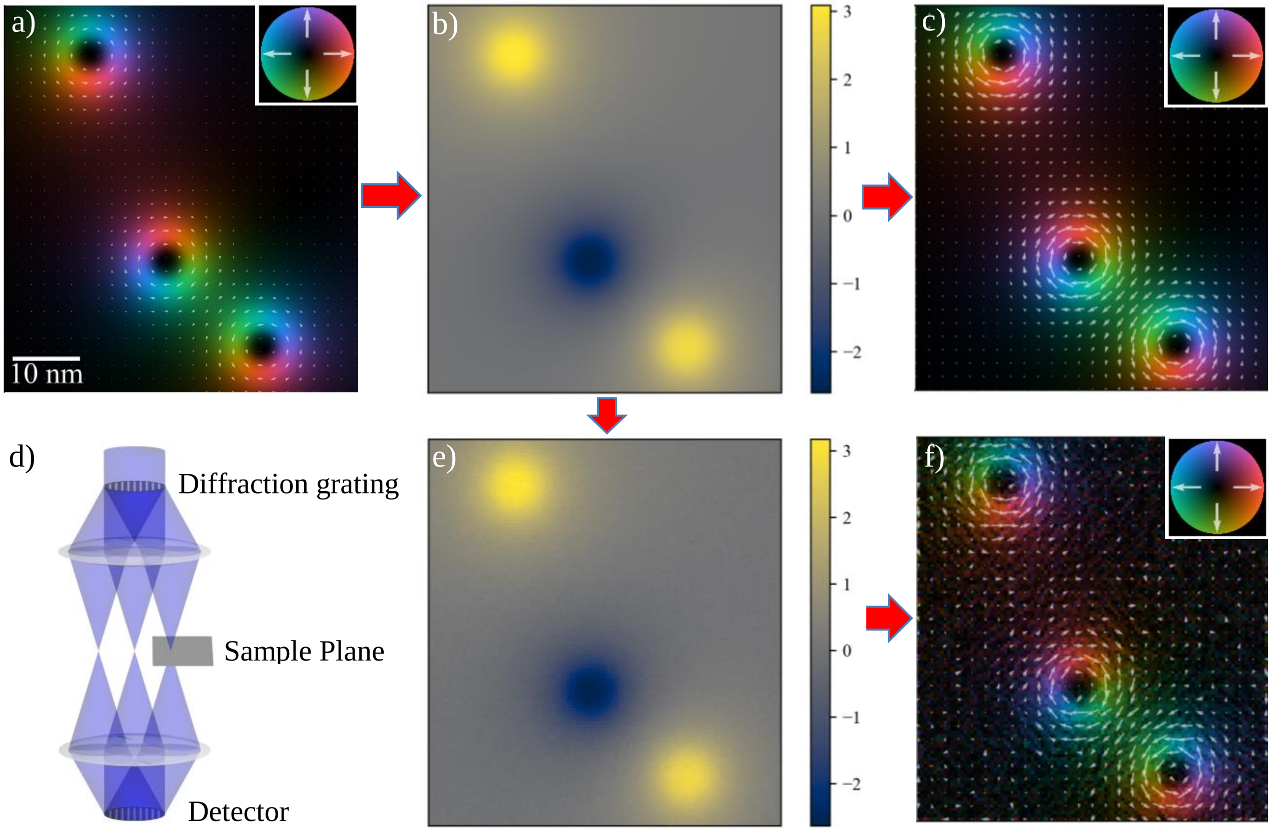

Figure 1. Simulated LSTEMH of 3 Bloch skyrmions. a) Magnetization of simulated thin film. b) Phase shift imparted on electron beam by specimen. c) Magnetic induction of the sample. d) STEMH experimental setup. e) LSTEMH phase reconstruction. f) Magnetic induction calculated from LSTEMH phase reconstruction. Arrows indicate that the following image was calculated from the preceding one. The scale of each image is the same.