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Improved Phase Reconstruction for Magnetic Materials in a Low-Aberration Environment

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To increase the information storage density of the current magnetic recording media, it is necessary to improve the signal-to-noise ratio of the media by either decreasing the grain size of the material or by using a nanoscale bit-patterned media [1]. Currently the size range of the grains or patterned media is of the order of $6 - 7$ nm. The crystallographic and physical structure of such materials can be easily characterized by the current generation transmission electron microscopes (TEM), however, to characterize the magnetic structure at this length scale is difficult. Lorentz Microscopy (LTEM) coupled with phase recovery has been used frequently for such characterization. In this contribution, we intend to show that with a reduction of the aberrations in Lorentz mode, the attainable resolution for magnetic characterization by means of phase recovery can be improved significantly.

In conventional Lorentz Fresnel imaging, the small Lorentz deflection angle necessitates the use of a large defocus value (of the order of several microns) to reveal the magnetic contrast. This, in turn, results in significant image blurring, limiting the spatial resolution to about $10 - 15$ nm. In a manner similar to HRTEM, the Lorentz lens can be described by a contrast transfer function (CTF) in reciprocal space or a point spread function (PSF) in real space. Figure 1 shows a comparison of the amplitude of the PSF for different microscope configurations in Lorentz mode: (a) the uncorrected 300 kV Titan 80-300, with $C_s = 8400$ mm, $C_c = 52$ mm, and Scherzer defocus $\Delta f_S = 4980$ nm; (b) the uncorrected 200 kV JEOL 2100F equipped with a dedicated Lorentz pole piece with a $C_s = 108$ mm, $C_c = 20$ mm, and $\Delta f_S = 628.49$ nm, and (c) C_s-corrected Titan 80-300, with $C_s = 0.5$ mm, $C_c = 92$ mm, and $\Delta f_S = 38$ nm [2]. The lower limit of the delocalization radius ($R = C_s \lambda^3 g_{max}^3/4$ [3]) for the uncorrected Titan 80-300 is as much as $R = 174$ nm; and for the microscopes with improved C_s, it is reduced to a range of ≈ 1 nm. The removal of delocalization effects has significant consequences for the ability to perform phase reconstructions based on Lorentz Fresnel images.

To compare the improvement in phase recovery, experiments were performed on a square Permalloy island of 1 μm in size. Through-focus series were recorded at varying values of defocus on both a Tecnai F20, which has a similar Lorentz lens as the uncorrected Titan 80-300, and a JEOL 2100 F. Images were also recorded with the sample flipped upside down, to separate the electrostatic and magnetic phase shifts. Fig. 2(a) shows the expected theoretical values of the individual phase shifts, (b) shows the best result obtained from the Tecnai at a defocus of $\Delta f = 340$ μ, and (c) shows the result obtained from the JEOL 2100 F at a defocus of $\Delta f = 36$ μm. It is can be seen that the defocus required to obtain good phase reconstructions is reduced by an order of magnitude. It is evident that the improvement in C_s also improves the phase reconstruction, and this will have significant consequences for the study of nanoscale magnetic features. We will illustrate the phase recovery improvements using a number of examples observed on the microscopes listed above.

References
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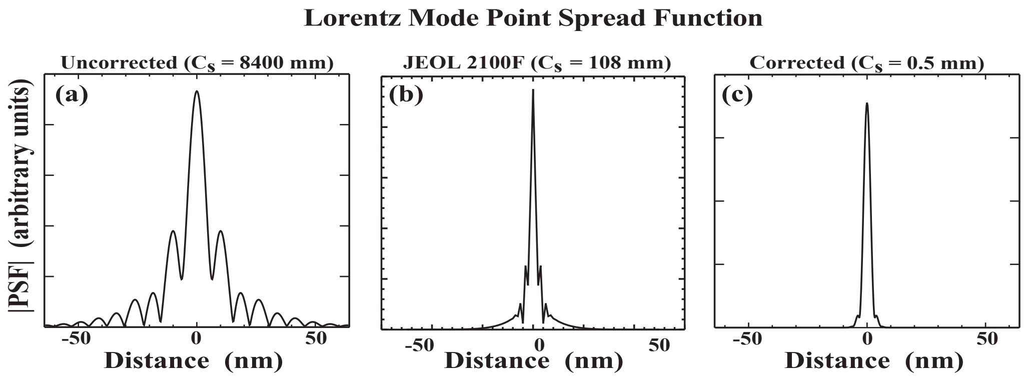

Figure 1: (a) Amplitude of the point spread function at Scherzer defocus for the (a) uncorrected Titan 80-300 in Lorentz mode, (b) uncorrected JEOL 2100 F, and (c) C_s-corrected Titan 80-300 in Lorentz mode. Note that the PSF does not include the detector PSF.

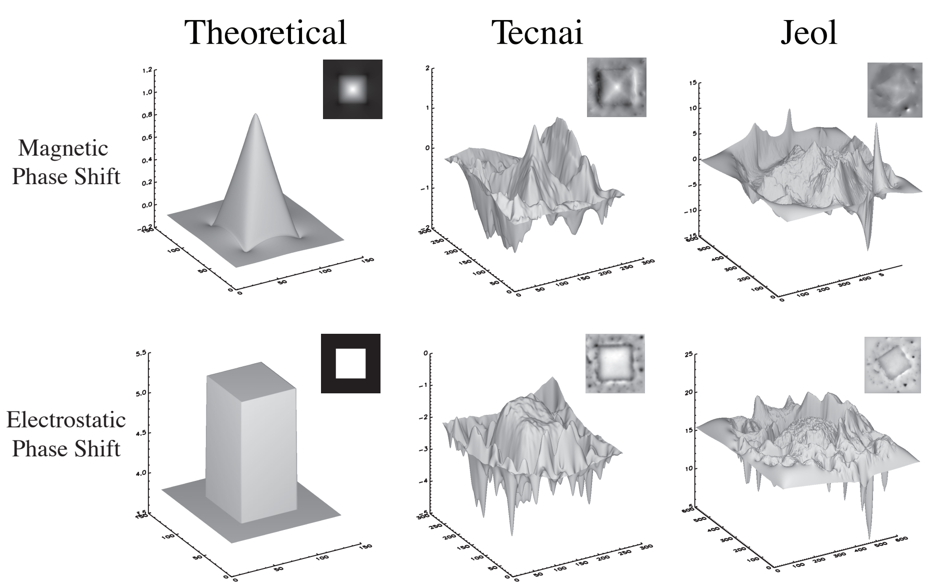

Figure 2: (a) The theoretical values of magnetic and electrostatic phase shifts for a square with closure domain magnetic configuration. (b) Shows the recovered individual phase shifts of a square Permalloy island with closure magnetic domain configuration from Tecnai F20 microscope using a defocus of $\Delta f = 340$ μm, and (c) shows the same results obtained on JEOL 2100 F using a defocus of $\Delta f = 36$ μm.

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