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# Image interpretation of magnetic domains in $Nd_2Fe_{14}B$ hard magnets

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Low magnification electron holography, combined with in-situ field-calibrated magnetization and demagnetization Lorentz or Foucault microscopy, provides a way to gain some insight regarding magnetization configurations in magnetic materials. However, the measured projected magnetization maps obtained as the gradient of the phase after the reconstruction from experimental data suffer several drawbacks. For instance, the phase shift induced depends not only on the local magnetic field inside and close to the specimen, which is the information we want to extract, but also on the fringing field in the vacuum. Moreover, the demagnetizing effect of the interfaces between material and vacuum at the specimen edges induce a bending of the holographic fringes which seems to indicate a dependence of the domain structure on the distance from the edge. It is thus worthwhile to analyze more accurately these features by a thorough theoretical analysis with image simulations to compare with the experimental micrographs like those presented in Fig. 1.

Recently a new Fourier-space approach for the calculation of the electron optical phase shift from long-range electromagnetic fields was proposed and discussed [1,2]. Let us consider a semi-infinite (i.e. demagnetizing effects of the edge included) periodic array of 180° stripe domains of width *w*, as shown in Fig 2. (a). By this approach it is possible to calculate the magnetic vector potential arising from the assumed magnetization configuration. Then, by integrating the vector potential along the electron trajectory, the phase shift can be calculated analytically [3] and compared with the experiments. The final result for the phase shift can be expressed as:

$$\varphi(x,y) = \frac{N_f}{\pi}\,\mathrm{Re}\left[2\,\Theta(x)e^{\pi iy/w}\Phi^2_{1/2}\left(e^{2\pi iy/w}\right) - \mathrm{S}(x)e^{\pi(iy-|x|)/w}\Phi^2_{1/2}\left(e^{2\pi(iy-|x|)/w}\right)\right]$$

where S($x$) is the standard Sign function, $\Theta(x)$ is the unit-step (Heaviside) function, $\Phi^s_v$ is a special function defined in [4], and $N_f$ is the number of flux quanta h/e (not necessarily an integer number, as the flux quantization does not apply here).

Up to now only domain walls of zero width were implemented in the model. However, the extension to a more realistic topography, like a Bloch or Néel wall between two opposite domains, can be achieved within the Fourier-space approach, and this improvement is the subject of present work. Here we test the validity of the model against experiments, which will provide also the basis for future accurate interpretations of phase shifts and phase contrast images of magnetic domains.

The phase shift of a pure magnetic origin (i.e. not including mean inner potential and thickness) is displayed in Fig. 2 (b) as a holographic cosine-plot, corresponding to the observation of a holography experiment shown in Fig. 1 (b).

With the algorithm it is also possible to calculate the main features of phase contrast images, such as out-of-focus (Fresnel contrast), where the domain walls are observed as interference fringes, or Foucault contrast, where the domains are seen as bright or dark regions. An example of a comparison between theory and experiment is reported in Fig. 1 (c)-2 (c) and in Fig. 3 (a,b).

Such a quantitative analysis can give us useful information on the capabilities of the techniques developed, especially on the ability of accurate measurements of the magnetization inside the domains, as well as across the domain walls.

References


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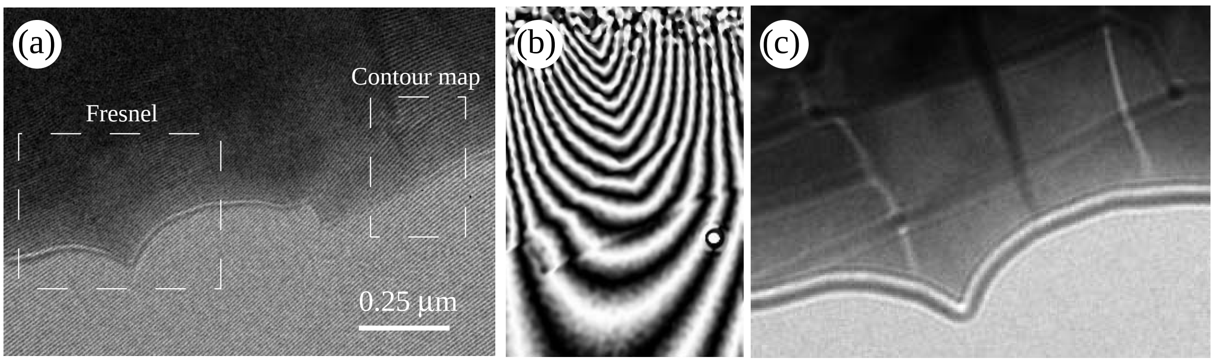


FIG. 1. (a) Electron hologram of a $Nd_2Fe_{14}B$ permanent magnet; (b) corresponding reconstructed phase shift (displayed as cosine map) and (c) Fresnel image from the regions marked in (a).

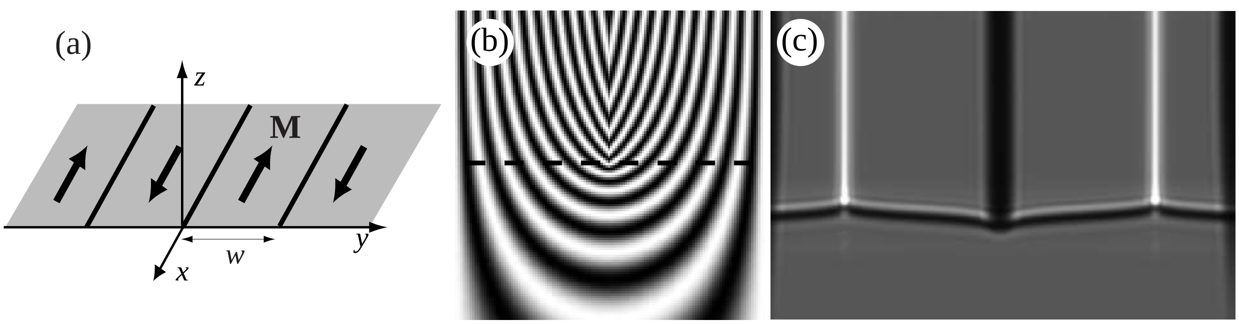


FIG. 2. (a) Magnetic configuration of the specimen: a semi-infinite array of 180° domains; (b) calculated phase shift displayed as a holographic cosine-plot; (c) calculated Fresnel contrast image.

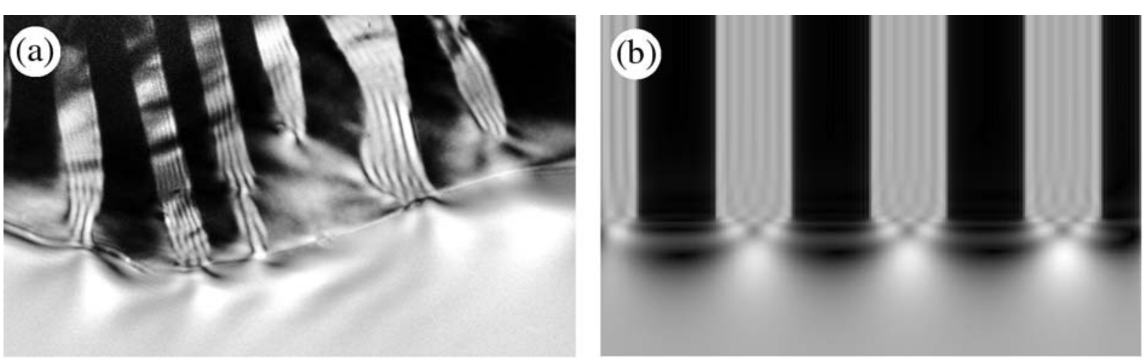


FIG. 3. Experimental Foucault image of an array of domains (a) and corresponding simulation (b).

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