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Modified Transport-of-Intensity Approach for Electrostatic and Magnetic Phase Shift Separation

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The structure of the magnetic field of nanoscale magnetic materials is of great importance in several areas, such as spintronics, magnetic memory alloys, and biomedical applications. Several methods exist that can quantitatively reconstruct various components of the magnetic field. Magnetic force microscopy measures the out-of-plane component of the magnetic field, while Lorentz microscopy and electron holography measure the in-plane components. Lorentz microscopy and electron holography both reconstruct the Aharonov-Bohm phase shift [1] of the electron wave. This phase shift consists of an electrostatic and magnetic component, which are the projections of the electrostatic potential V and the magnetic vector potential $\mathbf{A}$, respectively. To study the magnetization state of an object, it is necessary to separate these two phase shifts. Typically this requires application of time reversal symmetry, i.e., performing the reconstruction for the sample in normal orientation and flipped upside down and then subtracting the reconstructed phases. In this contribution, we describe an alternative approach in which the separation is accomplished before the phase reconstruction is carried out.

In Lorentz microscopy, the total phase shift is computed from a through-focus series of images via the Transport of Intensity Equation (TIE) [2], $\nabla \cdot [I(0)\nabla\varphi] = -k\partial_z I$ ($k = 2\pi/\lambda$) which relates the phase shift φ to the change in image intensity with defocus $\partial_z I$. To separate the phase shift components, the time reversal symmetry is applied as usual, but the subtraction is performed on the images themselves, instead of on the reconstructed phases. This leads to the definition of two different intensity derivatives:

$$\partial_z^e I = \frac{1}{4\Delta f}(I_+^+ - I_-^+ + I_+^- - I_-^-) \qquad \partial_z^m I = \frac{1}{4\Delta f}(I_+^+ - I_-^+ - I_+^- + I_-^-),$$

where the superscript indicates the orientation of the sample and the subscript the defocus $\pm\Delta f$. This leads to two Transport-of-Intensity equations:

$$\nabla \cdot (I_0 \nabla\varphi_e) = -k\,\partial_z^e I; \qquad \nabla \cdot (I_0 \nabla\varphi_m) = -k\,\partial_z^m I;$$

which can each be solved separately and result in the electrostatic φ_e and magnetic φ_m phase shifts. It should be noted that the electrostatic phase shift can be related to the projected charge density via the relation $\rho_p = \frac{\epsilon_0 k}{|e|\sigma}\partial_z I^e$ so that knowledge of $\partial_z I^e$ is sufficient to determine ρ_p, without having to actually solve the equation.

We have applied the new approach to phase reconstructions of rectangular CoFeB islands. The islands in Fig. 1 are $5 \times 1\mu\text{m}^2$, and 100 nm thick, and contain several magnetic domains. Fig. 2 shows the phase shift component reconstructions. φ_m changes at the domain boundaries within the sample and at the surface, and φ_e vanishes outside the sample, apart from scattered ion milling debris. Fig. 3 shows the projected induction reconstructions for the old and new methods, using the same data set. The new method results in an improved delineation of the magnetic domains in the sample compared to the old approach. Additional examples of the new approach will be provided.

References

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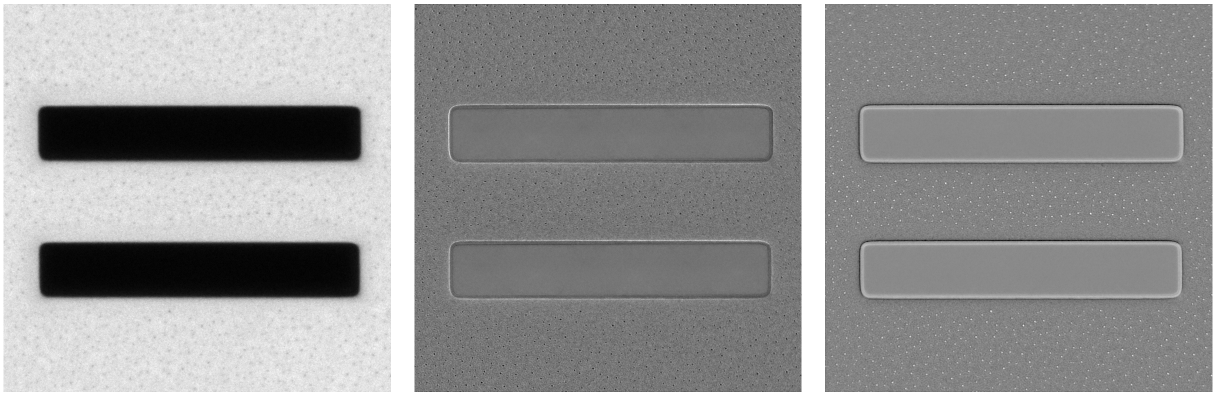
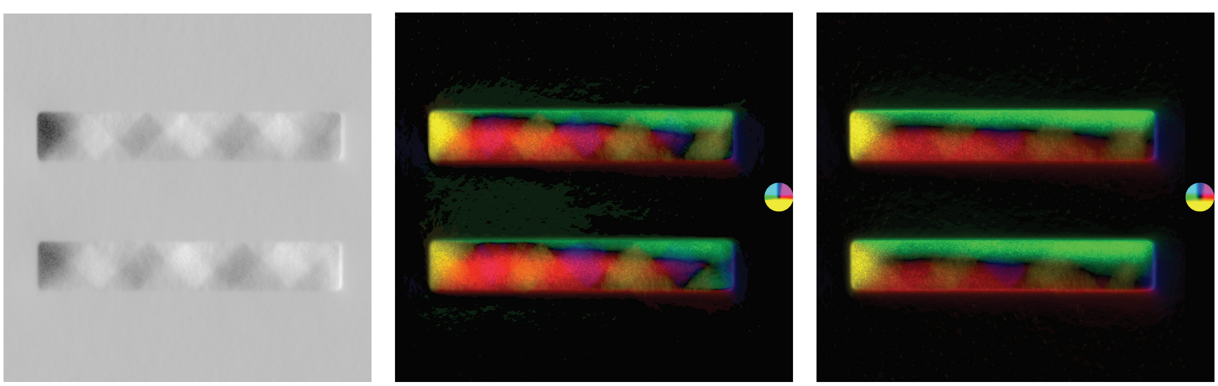


(a) In-Focus Image (b) $\partial_z^m I$ (c) $\partial_z^e I$

Figure 1: Aligned TEM image stacks of a pair of CoFeB islands.

(a) Total phase shift (old method) (b) Electrostatic phase shift φ_e (c) Magnetic phase shift φ_m

Figure 2: Phase shift component comparison.



(a) B_y induction component (b) Color plot of magnetic induction using our current method (c) Color plot of magnetic induction using the old method

Figure 3: Magnetic induction using our current method and the older method. Color indicates the magnitude and direction of $\mathbf{B}$.

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