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Reconstruction of Projected and 3D Magnetization Distributions from Electron-Optical Phase Images using an Iterative Model-Based Algorithm

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Off-axis electron holography is a powerful technique, which can be used to record the phase shift of an electron wave that has passed through an electron-transparent specimen in a transmission electron microscope. According to the Aharanov-Bohm equation, the phase shift is sensitive to local variations in electromagnetic potential, which are in turn dependent on nanoscale properties of a specimen of interest, such as charge density or magnetization. The measurement of such properties is important for many scientific fields, such as biomedicine, catalysis and data storage. However, their determination from a recorded phase image is in most cases an ill-posed problem that is difficult to tackle. Here, we describe the development of a model-based iterative reconstruction technique, which can be used to retrieve the projected in-plane magnetization distribution from the magnetic contribution to a recorded phase image, or alternatively the three-dimensional magnetization distribution from a set of at least two tilt series of magnetic phase images [1]. The technique is based on the optimized implementation of a forward model, which maps a given magnetization distribution onto one or more phase images. The forward model utilizes sparse matrix multiplications for efficient projections and subsequent fast Fourier-transform-based convolutions with pre-calculated convolution kernels based on analytical solutions for the magnetic phase images of simple geometrical objects. The ill-posed problem is tackled by first replacing the original problem by a least squares minimization, which is augmented by regularization techniques to find a unique solution for the reconstructed magnetization distribution. Tikhonov regularization of first order is used to apply smoothness constraints to the magnetization, which is justified by the minimization of exchange energy. In addition, *a priori* information about the positions and sizes of magnetic objects in the field of view are utilized in the form of a three-dimensional mask, which significantly reduces the number of unknowns to be retrieved. The model-based approach is highly flexible and can account for arbitrary linear phase ramps and phase offsets, as well as for untrustworthy (low confidence) regions in input phase images. We have applied it successfully to reconstruct in-plane magnetization distributions from experimental magnetic phase images and three-dimensional magnetization distributions from tilt series of phase images. Diagnostic measures, which are based on optimal estimation theory, have been used to analyze the quality of the reconstruction results. The influence of the regularization strength has been assessed, in order to obtain the best solution in the presence of noise and other artefacts. A representative example illustrating the reconstruction of the projected in-plane magnetization in four lithographically patterned Co elements from a single experimental magnetic phase image is shown in Fig. 1 [2].

References:

[1] J. Caron, Model-Based Reconstruction of Magnetisation Distributions in Nanostructures from Electron Optical Phase Images, Ph.D. thesis, RWTH Aachen University, 2017.
[2] The authors thank M Beleggia, G Pozzi, Z-A Li, M Riese and M Farle for contributions to this work.

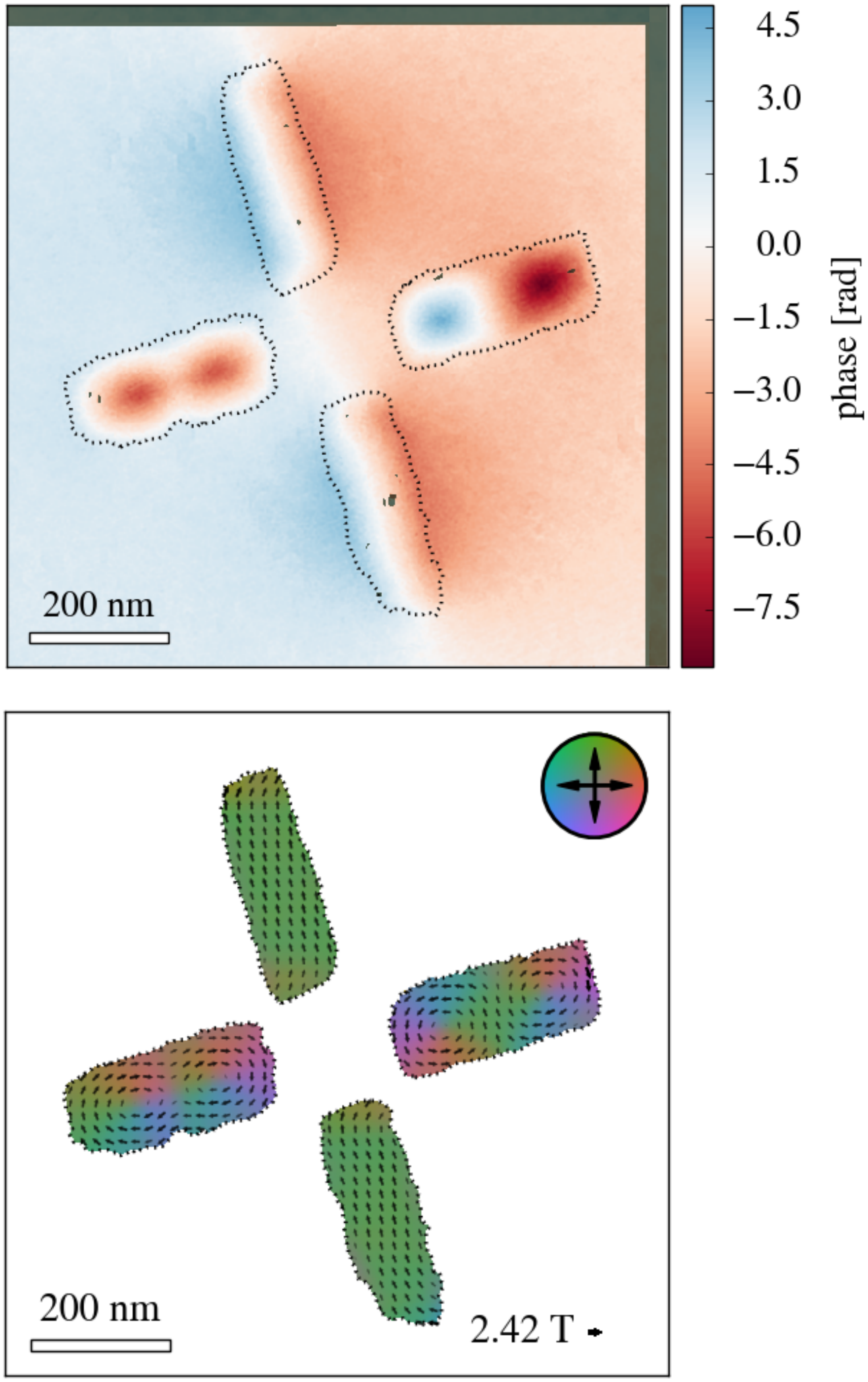

Figure 1. (Top) Experimentally recorded magnetic contribution to the electron optical phase of four lithographically patterned Co elements, which are marked by dotted lines, measured using off-axis electron holography. The mean inner potential contribution to the phase has been subtracted from this image. The shaded areas mark regions of low confidence that are excluded from the reconstruction. (Bottom) Projected in-plane magnetization reconstructed using model-based iterative reconstruction. Colors and arrows indicate magnetic vortex structures and homogeneously magnetized regions.