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IT-11-P-1940 Experimental evaluation of magnetic phase reconstruction in Lorentz TEM using the 'transport-of-intensity' equation

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Imaging the micromagnetic structure of materials at the nanometer scale is motivated by the scientific study of new magnetic phenomena, and the technological drive for new information storage devices, which increase the storage density.
The micromagnetic structure can be imaged using transmission electron microscopy (TEM) in a variety of contrast modes, termed 'Lorentz TEM'; for example, Fresnel-contrast (defocused images). Magnetic imaging in the TEM is possible because in the presence of a magnetic (and electric) potential, the electron wave-function undergoes a phase shift. Therefore, for quantitative mapping of the magnetic induction, the phase shift of the electron-wave needs to be reconstructed.

The 'transport-of-intensity' equation (TIE) is a general phase reconstruction methodology that can be applied to Lorentz TEM through the use of Fresnel-contrast images. We present an experimental study of sub-micrometer sized Permalloy elements in order to test the application of the TIE for quantitative magnetic mapping. We find that quantitative phase reconstructions (e.g. Fig. 1) are possible for defoci distances ranging approximately between 200 and 800 µm. The lower defocus limit is attributed to competing sources of image intensity variations in the Fresnel-contrast images such as structural defects and diffraction contrast. The upper defocus limit is shown to originate from a numerical error in the estimation of the intensity derivative.

Three sources of magnetic phase information are compared: domain walls, element edges and vortex cores. The vortex cores are shown to enable quantitative phase reconstructions while the domain walls and element edges enable only qualitative phase reconstructions. Considering the above limitations, we show quantitative reconstructions of elements sized down to approximately 100 nm and 5 nm thick. Thus, the minimal detection of the product of the magnetic induction and thickness is 5 Tesla·nanometer and magnetic structures are spatially resolved down to a size of 12 nanometers.

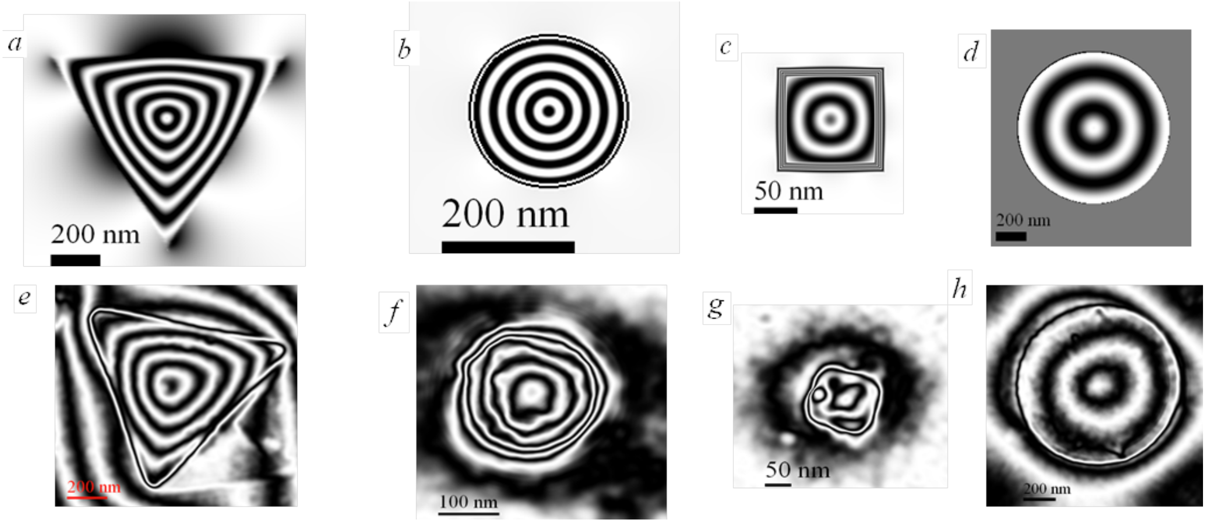

Fig. 1: Calculated (a, b, c, d) and experimental (e, f, g, h) eqi-phase contour maps (spaced at 1 radian) for Permalloy elements: triangular, 1µm diagonal, 10nm thick (a, e), circular, 250nm in diameter, 20nm thick (b, f), square, 130nm edge, 10nm thick (c, g) and circular, 1µm in diameter, 5nm thick (d, h).