Electron Beams with Helical Wavefronts and Quantized Angular Momentum

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We generated beams of electrons that carry quantized orbital angular momentum in a TEM using nanofabricated diffraction holograms[1]. Electron vortex beams are analogous to optical vortices such as Laguerre-Gaussian beams, but are composed of free electrons with helical wavefunctions and quantized orbital angular momentum. Unlike optical vortices, these beams possess magnetic properties due to the orbital motion of charged particles in free space. Electron vortex beams can be applied to new techniques in electron microscopy and offer fundamental insights into quantum behavior and electromagnetism.

The nanoscale diffraction gratings used to generate the beams (Fig. 1) consist of patterns with 20 nm feature sizes milled through a 30 nm suspended silicon nitride membrane using a focused ion beam (FIB). The mask pattern, spanning a circular area 5 μm in diameter, is a grating with a fork dislocation that encodes a topological phase singularity. In a TEM, this pattern is imprinted upon the de Broglie wavefronts of a spatially coherent beam of 300 keV electrons transmitted through the hologram. The electrons then diffract into multiple vortex beams (Fig. 2) that are each composed of electrons with helical wavefronts and quantized orbital angular momentum. The technique can be used to impart arbitrary amounts of quantized orbital angular momentum to free electrons. We demonstrated beams with up to 100 $\hbar$ quanta of angular momentum per electron.

Free electron beams carrying orbital angular momentum, enabled by diffractive optics for electrons, provide a promising new tool for electron microscopy. They can be used to image magnetic materials, using an inelastic exchange of quantized angular momentum from the beam to magnetic atoms in a sample. Electron vortex beams can also be used for phase contrast enhancement of electron-transparent objects in a TEM such as biological materials, by implementing the spiral phase microscopy technique recently developed in optical microscopy. Electron vortices could also be used to manipulate samples, such as inducing torque and eddy currents in materials or effectively applying magnetic fields at the nanoscale. Many of these applications will require electron beams with large angular momentum, similar to what we have demonstrated.

[1] B. J. McMorran, A. Agrawal, I. M. Anderson, A. A. Herzing, H. J. Lezec, J. J. McClelland, and J. Unguris, Science *in press*, (2011).

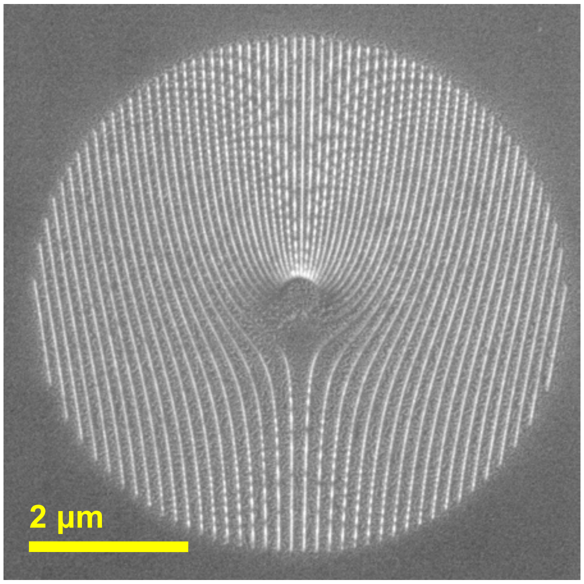

Figure 1: Nanofabricated hologram for electrons: In this SEM image, the light areas are slits milled through a silicon nitride membrane. The grating features a severe fork dislocation formed by an extra 25 slits in the top part of the grating. To preserve structural integrity where all these slits meet, a small circular area of material has been left at the center of the hologram.

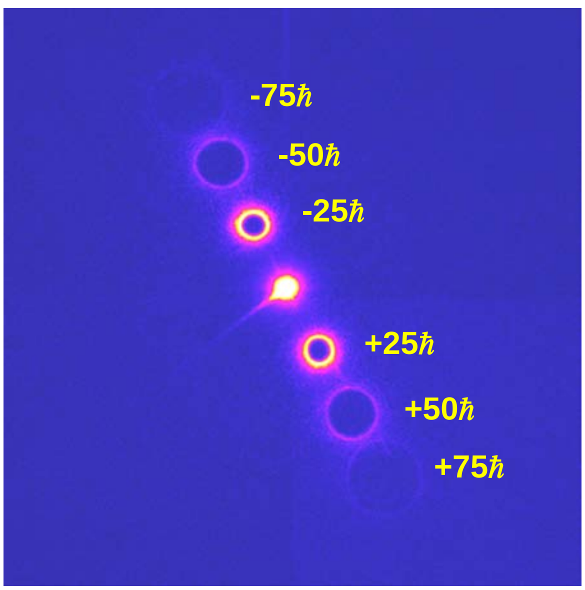

Figure 2: Electron vortex beams: Intensity profiles of multiple electron vortex beams projected onto an imaging detector. A false color scale has been applied to make the higher orders more evident. The multiple beams are generated by electron diffraction from the grating in Fig. 1, labeled by the amount of orbital angular momentum per electron relative to the beam axis. The central bright beam carries no orbital angular momentum.