Electron Mode Conversion and Vortex Generation

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Introduction

Since electrons and light can be described as propagating waves, there is potential for mutual inspiration and knowledge transfer between laser and electron beam physics. Laser beams can be mode converted between rectangular patterned Hermite profiles and radially symmetric Laguerre profiles by a pair of cylinder lenses, if the physical diameter of the beam, the distance between the lenses and the wavelength fullfill the conditions of mode matching [1]. The curvature of the phase front as well as the lateral extent have to be radially symmetric. See the illustrations in figure 1.

There are, however, fundamental challenges when such an optical mode converter is to be realized for electron beams. In particular the absence of cylinder lenses as well as true Gaussian sources for electron beams requires modifications of the setup. Spatially confined transient mode conversion of electrons has been demonstrated at a plane in between the two astigmatic line foci [2]. Here, we demonstrate a design for a close analogue to the optical mode converter which acts as a loss-less non-astigmatic vortex generator for electron beams.

The most appealing aspect of this approach to a vortex generator is the attainable maximal yield of fully converting the entire beam to a vortex state, without the need for astigmatism in the probe. Moreover, the electromagnetic quadrupoles can be freely rotated to prepare left and right handed vortices easily.

Methods

We propose to employ a Hilbert plate to prepare an incoming quasi Hermite(1,0) beam and to use the quadrupoles of a DCOR probe corrector from CEOS to realize a mode converter that

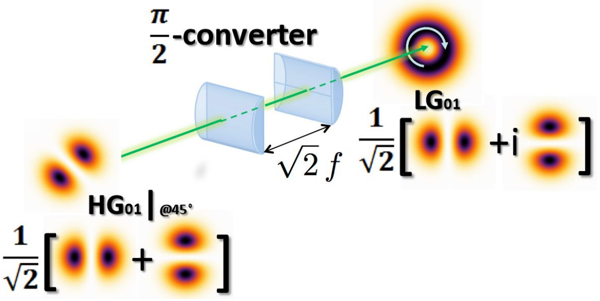

Figure 1: An optical mode converter transforms Hermite to Laguerre Gaussian profiles and vice versa. https://commons.wikimedia.org/wiki/File:Mode-converter.png

avoids any astigmatism in the mode converted beam. The vortex is formed inside the corrector, and maintained thereafter.

We have developed a simulation software for wave propagation that can handle multiple optical elements and spacings in between them. Apertures, lenses and quadrupoles can be inserted, removed, shuffled around and modified. All optical elements in the simulation are represented by two dimensional complex absorbers and/or phase shifters. The propagation from one optical element to the next is calculated by Fresnel propagation in Fourier space. The latter is well justified for wavelengths of 2.5 pm (at 200 keV), beam diameters of μm and distances of cm.

Results

The optical setup was chosen to closely resemble the actual geometry of the PICO microscope at the ER-C in Jülich. In the simulated setup, we consider a round 10 μm aperture at the second condenser lens (C2). The third condenser lens (C3) is turned off, and the C3 aperture holds a Hilbert plate. We would like to point out that the suggested setup is stable with respect to minor changes ($\leq$1%) in lens excitation and even the inclusion of a 1 μm wide absorbing bar at the Hilbert plate can easily be compensated.

Figure 2 shows two equivalent electron beams for two different kind of Hilbert plates. For numerical reasons (pixel size 8 nm) the objective lens has a focal length of 30 mm. The simulated vortices are expected to be 10 to 15 times magnified compared to actual objective excitations. A notable characteristic is the flat phase after the adapter lens (ADL) at the entrance of the DCOR, which defies the expectations from simple Gaussian beam propagation and also geometric optics. In geometric optics, the ADL would have to be focused onto the 2^{nd} quadrupole, in order to mimic the optical mode converter. These strong deviations from classical behavior are only expected for $\leq 1\,\mu$m wide electron beams, and become negligible around 3 μm width.

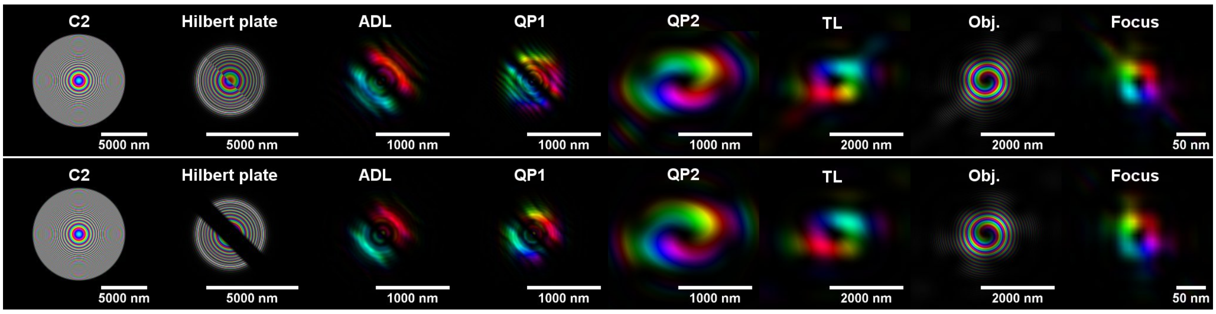

Figure 2: Phase colored beam profiles at 200 keV. With (bottom) and without (top) a central bar in the Hilbert plate. Cross sections in the rows are after the C2 aperture, Hilbert plate, adapter lens (ADL), 1^{st} quadrupole (QP1), 2^{nd} quadrupole (QP2), transfer lens (TL), objective lens (Obj.) and, lastly, in the focus.

Discussion

The required beam diameter of just under 1 μm or apertures below 1 mrad are definitely outside the realm of normal electron microscope operation. In normal operation, when the Fresnel number is $\geq 10^4$, electron beams are well described as Gaussian beams or even by geometric optics. The mode converter operates at the far end of the near field regime where geometric optics utterly fail and substantial deviations from Gaussian optics are observed. The intermediate range with Fresnel number ≥ 10 shows phenomena such as interference between aperture fringes and Airy fringes and defies in many places conventional intuition. We believe that the simulation of the intermediate near field wave propagation will greatly assist the experimental venture into the realm of coherent sub milliradian e-beam optics in search for an equivalent of the optical mode converter.

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