Progress towards a Zernike Phase Plate for Electron Microscopy using a Focused Laser Beam

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Phase contrast in transmission electron microscopy (TEM) produces images of weakly scattering phase objects, such as thin biological specimens, by converting phase modulation of the electron’s wavefunction into amplitude modulation, and thus into an image. A Zernike phase plate in the back focal plane of the objective lens achieves this by imparting a $\pi/2$ phase shift to the undiffracted component of the electron’s wavefunction, which is then translated into an image through interference with the diffracted components [1]. Current phase plates, such as carbon films and electrostatic einzel lenses, degrade during use due to charging by the electron beam [1]. We propose a Zernike phase plate realized using the focus of a CO₂ laser [1]. Using a laser beam as a phase plate avoids charging effects and allows for optical alignment and a tunable phase shift.

In the experimental set-up, an approximately 100-W CO₂ (Apollo 150) laser will be focused by a parabolic mirror installed in the TEM (FEI Titan). The electrons will travel through the mirror’s focus and will be phase-shifted by the ponderomotive potential of the laser by

$$\phi = \left( \frac{P}{\lambda} \right) \left( \frac{\lambda}{\mu m} \right) \left( \frac{V}{c} \right)^{-1} \frac{N}{\gamma(1-r_{\text{eff}})}.$$  

The needed phase shift can be achieved with wavelength $\lambda = 10.6$ μm, laser power $P = 80$ W, focusing lens calibration factor $N = 0.15$, effective reflectivity of the parabolic mirror $r_{\text{eff}} = 90\%$ and 300 keV electrons having Lorentz factors $\gamma = 1.6$ and velocities $v = 0.8c$, $c$ is the speed of light.

As proposed, this setup uses the parabolic mirror as the end mirror of the laser cavity. The parabolic mirror then needs to be excited with a ring mode in order to satisfy resonance conditions. Ring modes can be created by placing a pair of identical axicon lenses within the cavity. The first axicon turns a Gaussian profile into a ring, which is then collimated by the second axicon.

To create a relative phase shift between the undiffracted and diffracted components of the electron’s wavefunction, the laser intensity must be large for the undiffracted component but near zero for the diffracted components. The parabolic mirror creates a small, steep focus, thereby allowing contrast for low spatial frequencies. In our particular TEM (FEI Titan), a cut-on spatial frequency of 1/36 nm is achievable with the laser focused to a 4.6 μm diameter.

In the near future, we will trap atoms in an optical dipole trap at the focus to verify the predicted focusing capabilities of the parabolic mirror. Atomic energy levels are perturbed in the presence of radiation; the correction to the energy is known as the AC Stark shift. Probing the AC Stark shift of atoms at the focus will reveal the spatial distribution and intensity of light focused in the mirror. The laser phase plate set-up can be fully integrated into the TEM for phase contrast imaging when the focusing properties are confirmed.
This poster demonstrates the progress made thus far on the laser-enabled Zernike phase plate. Specifically, we will describe the simulations performed on the resonance conditions of the parabolic mirror, the current progress of the optical dipole trap, experimental evidence of resonant cavities that incorporate the axicon lenses and the future applications of the laser phase plate.

References:
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Figure 1: Thermal image of the ring mode emitted from the laser cavity.

Figure 2: Simulations of the intensity profile at the focus (dashed window) of the parabolic mirror for various polarizations were performed for plane waves with a wavelength of 750 nm and a focal length of 5 μm (see Figure 3).

Figure 3: Simulation of the intensity at the focus of the parabolic mirror for various polarizations, noted by arrows at the top of each diagram (scale bar = 750 nm).

Figure 4: Intensity versus position for radial polarization. Plotted intensity is normalized to the input intensity, focus of the parabola is at (x = 0, z = 0).