Generation and measurement of high harmonics with orbital angular momentum

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Applying an angle dependant phase \( \phi = \ell \theta \) to a Gaussian beam creates a singularity at the center while converting the original flat phase profile to a Laguerre-Gaussian (LG\(_{p=0,\ell}\)) phase profile where \( \ell \hbar \) is the orbital angular momentum (OAM) of the mode [1]. If a diffraction-limited XUV or soft-X-ray beam with OAM can be created, then, when such a beam is focussed, we find a rapidly varying spatial intensity distribution that is ideally suited to excite quadrupole transitions [2]. Thus learning to impose a controlled orbital angular momentum on high harmonic beams opens these transitions for systematic study. We use a spatial light modulator (SLM) to create a femtosecond laser beam with a LG\(_{01}\) phase profile and convert this beam to the XUV via high harmonic generation (HHG).

We imprint a characteristic fork profile on the SLM to impart OAM to the femtosecond beam. This fork consists of two elements. The first is the angle dependent phase profile, and the second is a blazed grating whose purpose is to angularly separate the OAM beam from the reflected original mode. When focussing the pump to generate high harmonics, the two modes are thus spatially separated. For all of our studies, we use a long-period grating to minimize the spatial chirp at the focus of the femtosecond pulse. We have experimentally verified that we create an infrared beam with \( \ell = 1 \). The strong field approximation of HHG predicts that the phase profile of the \( n^{th} \) harmonic is \( \phi_n = n\theta \), giving rise to a beam of OAM \( n\hbar \).

The experimental intensity profiles were obtained using a XUV spectrometer to separate the different harmonics orders. The y-dimension is directly imaged onto a microchannel plate/CCD detector while we reconstruct the x-dimension by scanning the spectrometer slit across the harmonic beam in the x-direction. The experimental data (1(a)) has a very similar intensity profile as the predicted profile. The zero-intensity at its center is evident and is consistent with the presence of a singularity.

To experimentally confirm that the OAM is conserved during HHG, we also need to measure the harmonics phase profiles. We suggest to create two distinct harmonic beams, from the zero-order and first order of the SLM, and measure their interference pattern in the far-field. Figure 1(b) shows the pattern that the SFA predicts for the interference of two harmonic beams, one with \( \ell = 0 \) and the other with \( \ell = n \), in which we see a n-fork, indicating that the beam has \( n\hbar \) units of OAM. This technique will enable us to confirm the conservation of OAM predicted by strong field approximation.

(a) Experimental intensity profile. (b) Theoretical interference between \( \ell = 0 \) and \( \ell = n \) beams.

Fig. 1. a) Experimental results and b) proposed method to measure OAM for 15\(^{th}\) harmonic.