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Characterization of Highly Structured High Harmonic Beams through Multiplexed Broadband Ptychography

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Abstract: We demonstrate multi-modal transmission ptychography on high-order harmonic vector beams. The process retrieves highly structured beam profiles and wavefronts in addition to spectral resolution without grating dispersion.

1. Introduction

While high-order Harmonic Generation (HHG) has been an active area of research for some years, a better understanding of how the precise generation conditions affect the output wavefront and polarization structure is anticipated to lead to even more precise control of the high-harmonic beams. Robust methods of characterizing the fundamental driving laser and the harmonics produced are being developed. The short wavelength and the vacuum environment of the high-order harmonics (HHs) make it difficult to apply techniques that are common in the visible part of the spectrum. To address these obstacles, two main approaches have emerged in the field of HH beam characterization. Freisem et al demonstrated a spectrally-resolved Hartmann sensor for HH wavefront characterization [1]. These devices have been used for real-time feedback of the HHG process along with using the reconstructions to investigate the wavefronts at the generation plane of the harmonics. Another approach is a variant of computational imaging, ptychography, that has been used with HHG to recover phase and amplitude information of samples illuminated by either a specific harmonic or a combination of harmonics [2].

We use the power of multiplexed broadband ptychography [3] to characterize the harmonic-resolved complex beams without the use of any additional dispersion. Multiplexed broadband ptychography can simultaneously solve for multiple probe modes among each color reconstructed in the algorithm. The probe modes, after being spectrally separated, can be further deconvolved by beam components, such as polarization, that do not interfere with each other. In particular, vector beams are a combination of two spatial modes with orthogonal polarizations, thus each retrieved harmonic beam is seen to have two distinct modes. A simple change to the scanned mask allows the fundamental driving laser to also be characterized.

2. Experimental set up and analysis

Experiments presented here use a Solstice Ace from Spectra Physics. The system has a repetition rate of 1 kHz, central wavelength of 800 nm, a full width half max (FWHM) bandwidth of 40 nm, with a maximum pulse energy of 6 mJ. We use a BBO crystal to produce second harmonic generation at 400 nm which is then used to drive the HHG in a gas jet with orifice size of 150 μm dia, and Argon as the gas target. The harmonics are sent directly to a windowless CCD camera through two aluminium filters, each 350 nm thick, to block the driving laser. A 4-quadrant copper TEM mesh pattern is scanned across the harmonic beams while a different SEM copper grid is used for the fundamental beam. The TEM mesh pattern can be seen as an inset to the reconstructed object shown in Fig 1(c). To create the structured harmonics we use an s-waveplate designed and fabricated by the Kazansky Group at the University of Southampton. The s-waveplate can be used to convert a linearly polarized Gaussian beam into a Vector beam. With the use of two additional 1/4 waveplates the s-waveplate can also be used to make a linearly polarized Vortex beam. Using these experimental parameters, we can employ ptychography to investigate a variety of generation conditions with the driving laser taking the form of a Gaussian, Vector, or Vortex beam.

Of particular interest is the ability for the ptychography to investigate highly structured beams that current Hartmann sensors cannot resolve. One specific example is a Vector beam, where the structure comes in the form of a spatially dependent polarization state. Vector beams can be decomposed into two significantly different basis sets. One set is two Laguerre-Gaussian (LG) beams of opposite orbital angular momentum (OAM) charge and opposite circular polarization states (CP-LG). Another basis set is two Hermite Gaussian (HG) beams of orthogonal linear polarization (LP-HG). By providing probe guesses to the algorithm we can direct the reconstruction to either outcome with both providing low error solutions. We simultaneously let the ptychographic algorithm reconstruct 4 different wavelengths with two allowed modes per wavelength. This also allows the algorithm to reconstruct the modal weights for each wavelength and mode. We implement object averaging in the reconstruction to enforce

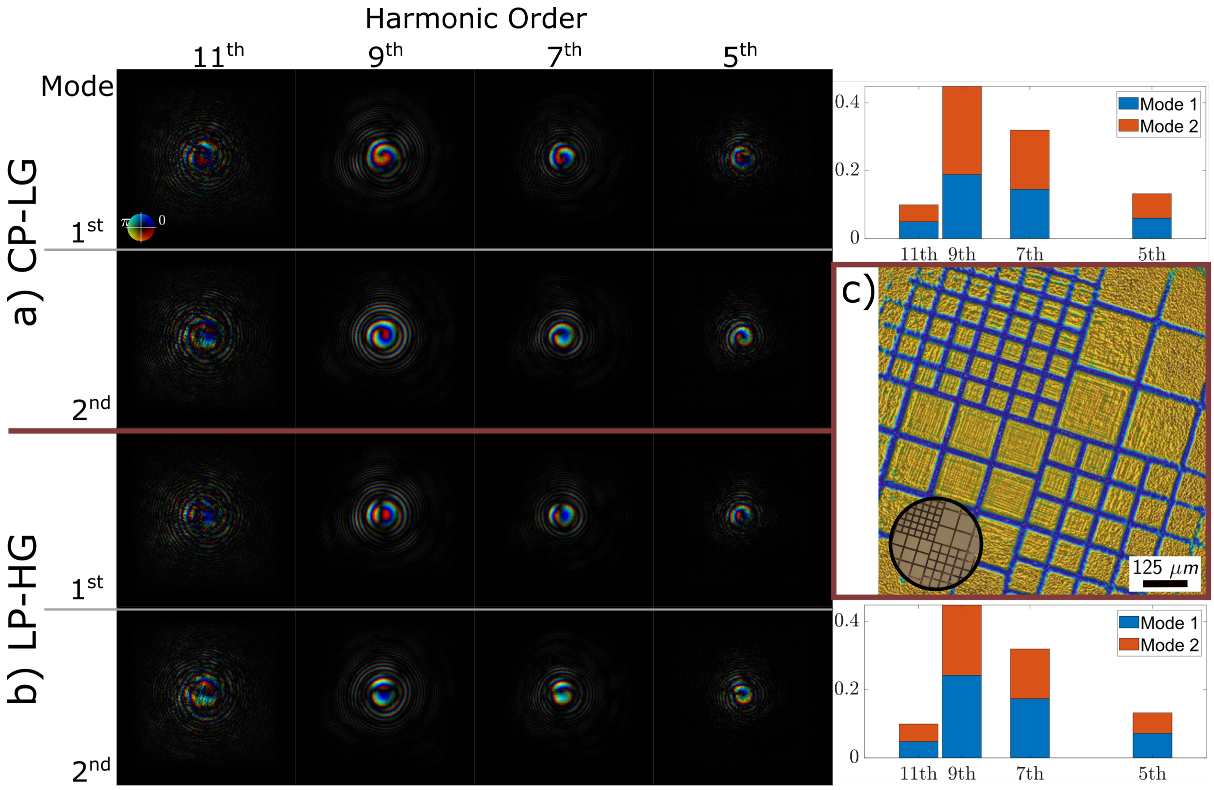

Fig. 1. a) A CP-LG reconstruction of the Vector beam. The probes are plotted with the hue representing the phase, and the brightness representing amplitude. b) A LP-HG reconstruction of the same beam showing that both decompositions are possible. The modal weights of each color and mode are shown on the right for each decomposition. c) The reconstructed object for the CP-LG decomposition shown with scale bar. The inset is a microscope image of the real object used in experiment.

that all wavelengths use the same object when reconstructing the probes. Fig 1(a,b) shows the results of the CP-LG and LP-HG reconstructions, respectively, for Vector harmonics produced by a 400 nm Vector driving laser. The reconstructed object for the CP-LG decomposition is shown in 1(c), a similarly high fidelity object is reconstructed in the LP-HG case and is not shown here.

In comparison to the EUV Hartmann sensor this method allows for higher spatial resolution, while giving up real-time results. A Hartmann sensor is limited by the number of holes in its diffractive mask to determine the wavefront spatial sampling resolution. Ptychography does not have this limitation and will have a reconstruction that scales as $dx = \lambda z/\delta x N$, where z is the distance from the object to the detector, δx is pixel size, and N is the number of pixels in one dimension of the detector. Due to the short wavelength of EUV light, our reconstructions have high spatial resolution with our experimental parameters yielding a resolution on the order of 1 μm for the harmonics. Hartmann sensors also require a precise calibration to report an absolute measurement of the wavefront instead of just a relative measurement. No such calibration is required in ptychography, with the reconstruction reporting an absolute measurement up to a constant phase offset. Finally, ptychography allows for a de-multiplexing of modes that a typical Hartmann device would not have the ability to resolve, allowing more complex and structured beams to be sampled in ptychography. With a method for reconstructing the full complex fields of both the driving laser and HHs, ptychography holds promise to inform an understanding of the generation mechanisms and points to routes for wavefront control of the HH.

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