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High topological charge extreme-ultraviolet vortex and vector-vortex beams

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Abstract: We demonstrate the production of EUV vortex beams, and vector-vortex beams merging the helical phase of a vortex and the spatially variant polarization of a vector beam, both carrying large orbital angular momentum per photon.

Light beams structured in their phase, and polarization have proven their usefulness for a wide range of applications [1, 2]. In particular, optical vortex beams carry orbital angular momentum (OAM) and they are characterized by their azimuthally twisting wavefront. The total wavefront twist in the transverse plane signifies the topological charge ℓ of the vortex beam. On the other hand, vector beams exhibit a spatially varying polarization that is encoded in their spin angular momentum (SAM). The combination of the twisted phase of a vortex beam and the spatially inhomogeneous polarization distribution of a vector beam is the vector-vortex beam (VVB) that is simultaneously structured in its SAM and OAM. We note that the topological charge of a VVB is rigorously defined through the Pancharatnam charge ℓ_p that accounts both for the SAM and the OAM of the vector-vortex beams [3]. Moreover, a VVB of Pancharatnam topological charge ℓ_p can be interpreted as a superposition of two circularly polarized optical vortices of opposite handedness (right circular RCP and left circular LCP) and distinct topological charges: $\ell_{RCP} = \ell_p + 1$ and $\ell_{LCP} = \ell_p - 1$.

Most recently, the high-order harmonic generation (HHG) in noble gases has led to the upconversion of the long-wavelength vortex and vector beams into the extreme ultraviolet (EUV) spectral regime [4, 5, 6]. Concerning OAM-driven HHG, the conservation law imposes a linear upscaling of the driving beam topological charge ℓ [4]: $\ell_q = q\ell$, where ℓ_q is topological of the q^{th} harmonic. In this work, we exploit HHG in 15 mm long Argon gas cell to generate EUV vortex beams exhibiting extremely high topological charge (up to $\ell_q = 100$), hence a very high value of OAM per photon [7]. In the next step, we drive HHG with IR vector-vortex beams to demonstrate that the selection rule for EUV vectorial-vortices obtained through HHG is governed by the upscaling of topological Pancharatnam charge and not the OAM of the constituent RCP and LCP modes [8]. We rely on EUV wavefront metrology to perform complete spatial characterization of intensity and wavefront of HHG vortex and vector-vortex beams, therefore unambiguously affirming their topological charge. On the one hand, EUV beams with a very high topological charge (see Fig. 1) open the possibility of OAM transfer from light to matter. On the other hand, the EUV VVB obtained through HHG offers the possibility to obtain attosecond light-springs with spatially variant linear polarization (Fig. 1g), which brings in a unique tool to study spatiotemporal dynamics in polarization-dependent systems.

In the left panel of Fig. 1, we show (a) the intensity and (b) the wavefront of uniformly polarized (vertical polarization) 25^{th} harmonic (central wavelength 32.6 nm) for IR vortex driver (central wavelength 815 nm) of $\ell = 2$. Remarkably, the wavefront in Fig. 1(b) shows a continuous twist of ~50 wavelengths, hence validating the expected scaling of topological charge with harmonic order for vortex-driven HHG. In the right panel, we present the experimental vertical polarization intensity component (c) and the wavefront (d) of the 25^{th} harmonic for the vector-vortex driving beam of Pancharatnam charge $\ell_p = 2$. In contrast to the uniformly polarized EUV vortex in (a), the vertical polarization intensity projection of HHG vector-vortex (c) displays two horizontal lobes, which indicates azimuthal polarization. Most importantly, the wavefront (d) manifests an azimuthal twist of ~50 wavelengths, hence affirming that for vector-vortex driven HHG, the Pancharatnam topological charge of the q^{th} harmonic scales linearly with the Pancharatnam topological charge of the driving beam. We compare the experimental characterization (c, d) to the results of full quantum SFA calculation of 25th harmonic in (e, f). The experimental and the theoretical results show an excellent agreement. In (g), the spatiotemporal structure of azimuthally polarized attosecond light-spring resulting from our full quantum calculations is presented. Notably, (g) demonstrates that spatiotemporal light-springs can be tailored to exhibit spatially variant polarization, hence offering a new degree of freedom for attosecond light beams.

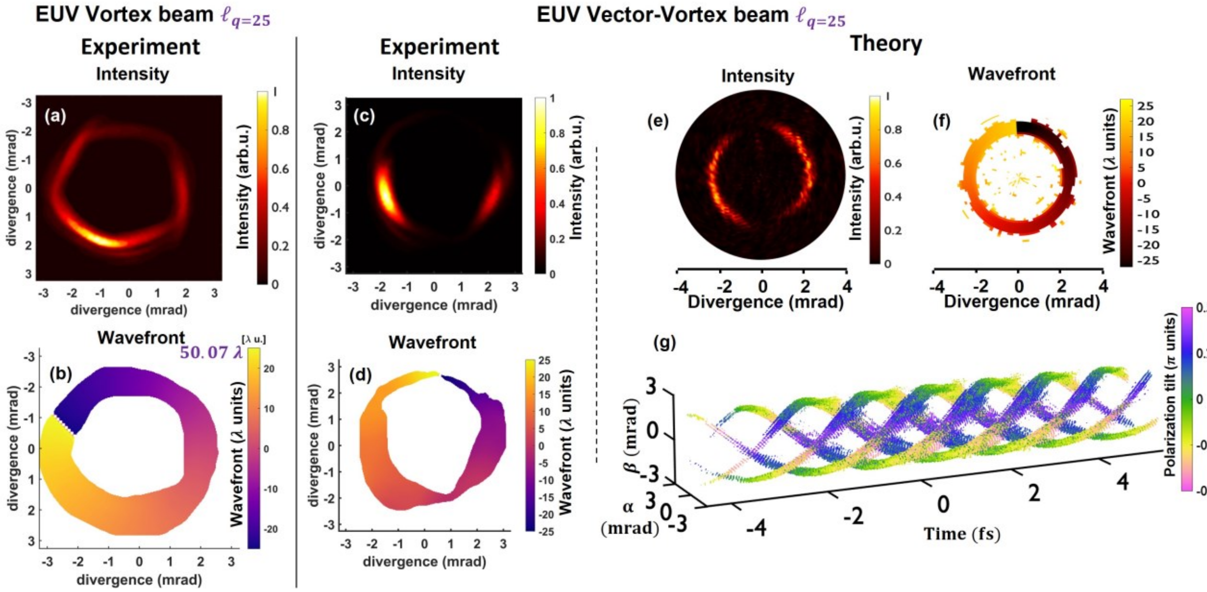

Fig. 1. Characterization of EUV vortex and vector-vortex beams carrying large OAM. Left panel: Experimental (a) intensity and (b) wavefront of the 25th harmonic driven by IR vortex beam of $\ell = 2$. Right panel: experimentally measured (c) vertical polarization intensity and (d) wavefront profiles of the azimuthally polarized EUV vector-vortex (25th harmonic). We compare the experimental characterization presented in (c, d) to the results of the full quantum SFA calculation of the 25th harmonic in (e, f). In (g), we depict the computed spatiotemporal structure of azimuthally polarized attosecond light-spring.

In conclusion, we experimentally and theoretically demonstrate the production of HHG vortex beams that are spatially structured in their phase, and HHG vector-vortex bearing combined characteristics of vector and vortex beams, both carrying high OAM value per photon.

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