Structuring Harmonic Vector-Vortex Beams in the Extreme Ultraviolet

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Abstract: The synchronous control of spin and orbital angular momentum in high-harmonic generation allows us to introduce experimentally and theoretically a novel XUV structured beam with spatially-varying polarization and phase, high topological charge, and robust propagation.

A vector-vortex beam presents both the twisted azimuthal phase of a vortex beam and the spatially inhomogeneous polarization profile of a vector beam. Hence, this singular structured beam merges the polarization and phase of vector and vortex beams, both of them widely used in diverse applications such as optical communications, quantum information, imaging, topological systems, magnetism, material processing, optical tweezers, particle acceleration, or light-matter interactions.

Engineering the phase and polarization properties of vector-vortex beams in the infrared or visible domain (IR) is feasible nowadays. A desirable pathway would be to extend their applications towards the short-wavelength regime, with the corresponding advantage of a higher temporal and spatial resolution. In this context, the coherent nature of high-order harmonic generation (HHG) is helpful, since it allows to map some of the properties of an IR driver into the extreme ultraviolet (XUV) or even in the soft x-rays. Previous works in the literature demonstrated the separate up-conversion of vector or vortex beams via HHG [1–3]. However, to our knowledge, this is the first work [4] exploring the generation of harmonic vector-vortex beams, implying a synchronous control of spin and orbital angular momentum (SAM and OAM).

Unlike vector or vortex beams, the up-conversion of vector-vortex beams shows a complex evolution along propagation. A vector-vortex beam is not an eigenmode of the propagation operator and thus, its shape and properties are modified during propagation. The IR driving vector-vortex beam transforms the simple distribution of the linear azimuthal polarization at the generating polarization plate (Fig. 1a) into a tangled distribution at the gas target (Fig. 1b), containing all the possible polarization states [5]. To gain further insight, we note that a vector-vortex beam with topological charge ℓ is a superposition of two vortex beams with counterrotating circular polarizations (RCP and LCP) and topological charges $\ell_{RCP} = \ell + 1$ and $\ell_{LCP} = \ell - 1$:

$$e^{-i\ell\phi}\left[\cos(\phi+\varphi)\,\boldsymbol{e_x} + \sin(\phi+\varphi)\,\boldsymbol{e_y}\right] = \left[e^{-i(\ell+1)\phi}\left(\boldsymbol{e_x} + i\boldsymbol{e_y}\right) + e^{-i(\ell-1)\phi}e^{i2\varphi}\left(\boldsymbol{e_x} - i\boldsymbol{e_y}\right)\right]\frac{e^{-i\varphi}}{2}\,, \quad (1)$$

where φ determines the tilt of the polarization plane ($\varphi = 0, \pi/2$ are radial, azimuthal) and ϕ represents the azimuthal coordinate. We have characterized the two circularly polarized vortex beams at the gas target (see Fig. 1b), showing that their different divergence and phase properties are responsible for the total beam's evolution.

Despite the complexity of the IR driving beam at the target, we demonstrate that the high-harmonic beam is generated with a simpler structure because HHG is only efficient in the region of low ellipticities [6]. Figure 1(c) displays the experimental and theoretical characterization of the 25th harmonic beam. On one hand, we show the intensity of the vertical polarization projection, pointing out the characteristic polarization structure of a vector beam. On the other hand, the wavefront twists around 50 wavelengths for a driver with topological charge $\ell = 2$, indicating that the harmonic topological charge is $\ell_{25} = 50$. Hence, the topological charge of the harmonic vector-vortex beam scales linearly with the harmonic order i.e. $\ell_q = q\ell$, in analogy with the selection rule for a pure vortex with homogeneous polarization [2]. Nevertheless, the selection rule for the harmonic vector-vortex beam is far from trivial, since the linear scaling applies to the topological charge of the harmonic vector-vortex beam —which is rigorously defined through the geometric Pancharatnam phase [7]— , not to the OAM charge of the circularly polarized components $\ell_{q,RCP} = q\ell + 1$ and $\ell_{q,LCP} = q\ell - 1$. In contrast, the conservation laws in HHG are imposed to the combination of photons from LCP and RCP modes in order to derive analytically the selection rule, in a situation similar to conical refraction [8].

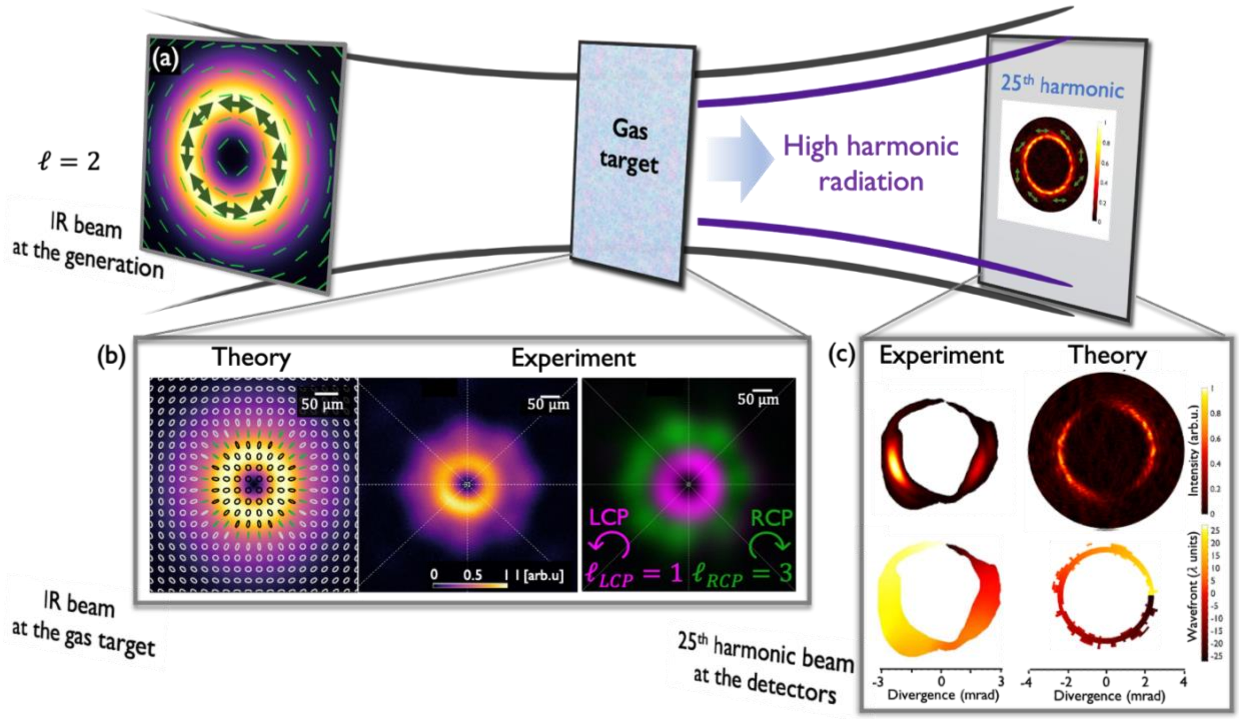

Fig. 1. Scheme of the up-conversion of vector-vortex beams via high harmonic generation. The IR vector-vortex beam is generated with a simple pattern of linear polarization (a) and evolves to a complex polarization pattern at the gas target (b). Since high harmonic generation is only efficient in the region of low ellipticities, the harmonic beam shows a clean distribution of nearly azimuthal polarization. In panel (c), we show the vertical polarization projection and the wavefront of the 25th harmonic beam.

In conclusion, we demonstrate the generation of coherent XUV vector-vortex beams through HHG. The selection rule results in harmonic vector-vortex beams with a high topological charge and a smooth propagation behavior, since the circularly polarized vortex components possess similar propagation properties for high topological charges.

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