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Conversion of a beam carrying fractionnal angular momentum in High-Harmonics Generation

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Abstract. Exotic light fields combining non-trivial spin and angular momentum may not be eigenstates of either the spin or orbital angular momenta operators. For these fields, it is relevant to define a Generalized Angular Momentum operator of which they are eigenvectors. Their associated eigenvalues can take, depending on the case, non-integer values. We report that this new quantity is conserved via non-linear phenomena, such as High Harmonic Generation.

1 Introduction

It has been known for a long time that light possesses an angular momentum which, in the paraxial approximation, can be divided into two components: the spin angular momentum (SAM) and the orbital angular momentum (OAM). They are respectively related to symmetries of rotation of the polarization and of the spatial distribution of the field. For the former, in this approximation, eigenmodes are the circularly polarized plane waves, with eigenvalues $\sigma\hbar$ with $\sigma = \pm 1$. For the latter, one possible basis of eigenmodes are the Laguerre-Gaussian modes, and the eigenvalues are $\ell\hbar$ with ℓ an integer.

However, some specific beams are eigenmodes neither of the SAM (S_z) nor the OAM (L_z) operators, but instead of a Generalized Angular Momentum (GAM) operator, as introduced lately by Ballantine *et al.* [4]. It is defined as a linear combination $J_{\gamma,z} = L_z + \gamma S_z$, where γ is a rational number which depends on the beam geometry. The eigenvalues associated with this operator are multiples of γ , and can thus take rational values, contrary to SAM or OAM.

While OAM and SAM have been extensively studied individually in non-linear optics for a while, the notion of GAM and what a non-integer angular momentum value could bring has attracted little attention. Indeed, no manipulation of the GAM was reported thus far, especially in non-linear optics. For such an objective, it is ideal to use an isotropic and homogenous non-linear medium to avoid breaking the symmetries of the beam. High Harmonics Generation (HHG) in gas is thus a perfect candidate for testing the sturdiness of GAM in non-linear optics.

Furthermore, the behavior of SAM and OAM individually [2, 3] or combined [5] in HHG is already well-known theoretically and experimentally. It was further predicted that the GAM should upscale linearly in HHG [6], but never demonstrated. Here, we report on the experimental demonstration and the development of an associated methodology [1].

2 Experiment and results

Our driving beam is a superposition of two different beams of the same wavelength, but carrying angular momenta ($\sigma = 1, \ell = 0$) and ($\sigma = -1, \ell = 1$). The relevant parameter here is $\gamma = \frac{1}{2}$. With it, their GAM is $j_{1/2} = 1 - \frac{1}{2} = 0 + \frac{1}{2} = \frac{1}{2}$, and so is the GAM of their superposition. This superposition creates an eigenmode of the GAM operator $J_{1/2}$ which is eigenvector of neither S nor L . The field we obtain has a polarization which goes from circular right on

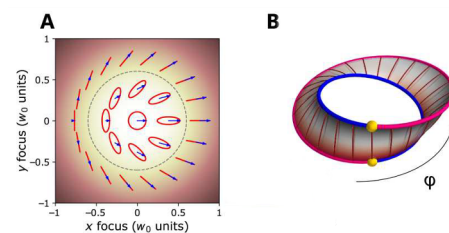


Figure 1. Topology of the driving field carrying a GAM $j_{1/2} = \frac{1}{2}$. **A.** Polarization ellipses (red) and vector at $t=0$ (blue) of the field. The background represents the field intensity. **B.** Polarization Möbius strip constructed by connecting the polarization ellipses along the dashed circle in **A**.

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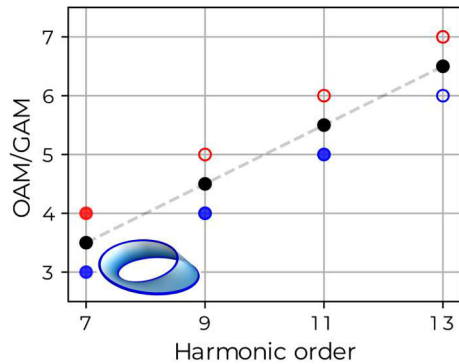


Figure 2. Each harmonic is made up of two components with opposite spin and different OAM (red and blue dots). However, their GAM $j_\gamma = \ell + \gamma\sigma$, if we take $\gamma = \frac{1}{2}$, is the same. Furthermore, it scales linearly with harmonic order, hence proving its linear scaling law in HHG.

the axis to circular left at infinity. In between, it is elliptical, and the polarization ellipses are turning half a turn along a circle centered on the beam axis, effectively forming a polarization Mobius strip (figure 1).

Complete characterisation of the angular momenta of XUV radiation is challenging due to the lack of transmissive optics. To achieve it, we introduced a small angle between the two driving beams. The generation point at focus is topologically the same as in a collinear geometry, but in the propagation downstream, the XUV generated will diffract in several beamlets with different properties. Actually, because of the circular polarization, only two beamlets will be generated [2]. We observed that these

beamlets have orthogonal polarizations. It was confirmed by numerical simulations, showing in addition that they should be circularly polarized, with opposite helicities. To measure their OAM, we tilted a spherical mirror to introduce astigmatism. It led to a partial mode conversion from Laguerre-Gaussian to Hermite-Gaussian modes. This created fringes inside the beamlet, whose number is related to the OAM carried by this beamlet. As is shown in figure 2, for each harmonic, we measured a different OAM on the two beamlets. However, if we compute their GAM with the same $\gamma = \frac{1}{2}$ as for the driving beam, we find that both beamlets of each harmonic have a GAM $j_{1/2} = \frac{q}{2} = qj_{1/2}^{\text{IR}}$.

These results open the way for a variety of investigations on fractional angular momentum in the XUV or in non-linear optics in general. We can envision for instance HHG in solids, where the medium is not isotropic and some polarization direction can be favored, or using an XUV field with fractional angular momentum to probe materials sensitive to combinations of spin and OAM.

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