High-Power Ultraviolet Vortex Beams Generated from a Relativistic Laser Interacting with an Ultrathin Foil

N. M. Fasano[1] and J. M. Mikhailova[1]

[1]Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey 08544, USA
nfasano@princeton.edu, j.mikhailova@princeton.edu

Abstract: Ultrathin foils irradiated by relativistic circularly polarized lasers emit harmonics in both the transmitted and reflected directions that contain orbital angular momentum. We demonstrate this scheme using ab-initio three-dimensional particle-in-cell simulations. © 2021 The Author(s)

1. Introduction

In addition to the well-known property of lasers that they can carry linear momentum, lasers can also carry angular momentum in the form of spin angular momentum (SAM) due to the laser's polarization state, as well as in the form of orbital angular momentum (OAM) due to the laser's helical wavefronts. Recent advances in high-power laser technology allows for creating optical vortices from relativistic light-matter interactions that can be useful for novel investigations of relativistic plasma dynamics [1-3].

In this work, we propose a scheme for generating a high-power, ultraviolet optical vortex beam through the interaction of a normally incident, circularly polarized (CP) laser with an ultrathin foil. Previous work has shown the utility of using CP lasers to drive solid density plasmas to induce harmonic orders of the laser's fundamental wavelength [4-6]. In particular, plasmas driven by normally incident CP lasers have been shown to generate optical vortex beams in the reflected direction using semi-infinite targets [5], and in the transmitted direction using micro-aperture targets [6]. Ultrathin foils, where the thickness of the target is much less than the laser wavelength, have been studied extensively in the context of radiation generation [7-9], and particle acceleration [10, 11], for their increased ability to couple laser energy with the plasma. Using three-dimensional particle-in-cell simulations, we demonstrate that, in both the transmitted and reflected directions, integer order harmonics carrying OAM are generated when a CP laser is normally incident on an ultrathin foil. The n^{th} order harmonic carries OAM of $(n-1)\hbar$ and SAM of $1\hbar$ in agreement with the conservation of total angular momentum.

2. Ultraviolet Vortex Beam from an Ultrathin Foil

To demonstrate the proposed scheme we use fully relativistic, three-dimensional particle-in-cell simulations [12]. Consider a relativistic circularly polarized laser normally incident on an ultrathin foil as depicted in figure 1a. The driving laser has a normalized laser amplitude of $a_o = eE_L/(m_e\omega_L c) = 40$ and has a gaussian profile in the transverse and longitudinal direction with a spot size of $w_o = 8\lambda_L$ and a full-width-half-maximum of $\tau = 10T_L$. The fully ionized target has a normalized plasma density of $n_e/n_c = 100$ and a target thickness of 32nm ($0.04\lambda_L$). The simulations have a spatial resolution of $\Delta x = 0.02\lambda_L$ and $\Delta y = \Delta z = 0.04\lambda_L$ and contain 8 computational particles-per-cell. A snapshot of the electric field is recorded and analyzed in both the transmitted and reflected directions for which the results are presented in figure 1b and 1c, respectively.

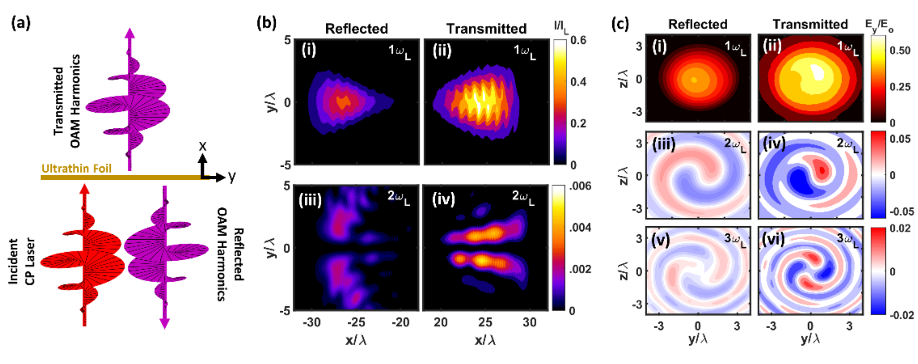

Figure 1: (Left panel) Schematic diagram of the proposed scheme. A circularly polarized laser is incident on an ultrathin foil and generated OAM harmonics in both the reflected and transmitted directions. (Center panel) Transmitted and reflected longitudinal beam profiles for both the fundamental and second harmonic. Here, we see the null intensity on the propagation axes of the second harmonic which is characteristic of vortex beams. (Right panel) Transmitted and reflected transverse beam profiles for the first three harmonics. The fundamental transverse profile is characterized by a Gaussian profile shape while the second and third harmonics contain the helical phase structure of topological charge 1 and 2, respectively.

Vortex beams which carry OAM are characterized by their helical phase fronts and their null on-axis intensity. For both the reflected and transmitted radiation, the on-axis electric field vanishes for the generated harmonics but not for the fundamental (fig. 1b). However, the presence of a singularity on-axis is not sufficient to conclude that the two beams have OAM – they must also contain the helical wavefronts. This is checked by analyzing a transverse slice of the propagating radiation (fig. 1c). Here, we can see that the generated harmonics contain the helical phase profile indicating OAM of topological charge 1 and 2 for the second and third harmonics, respectively. The fundamental beam transverse profile is still Gaussian and, as expected by the conservation of total angular momentum (SAM + OAM), all three harmonic orders are still circularly polarized. Thus, in both the reflected and transmitted direction we are left with n^{th} order harmonics with OAM of (n-1)ħ and SAM of 1ħ.

3. Plasma Dynamics

To understand these observations, we use the three-dimensional particle-in-cell simulations to study the plasma dynamics while the laser interacts with the ultrathin foil. For a circularly polarized driving laser at normal incidence there is no fast oscillation of the plasma surface. However, there still exists a radial force due to the pondermotive pressure. This creates a dented plasma surface (fig. 2a), for which subsequent off-axis laser cycles will locally experience an oblique interaction due to the plasma curvature [5]. At oblique incidence, the transverse component of a circularly polarized laser will drive longitudinal oscillations. These longitudinal oscillations rotate in the transverse plane with the polarization of the laser (fig. 2b), which leads to the emission of harmonics with the helical phase profile characteristic off vortex beams.

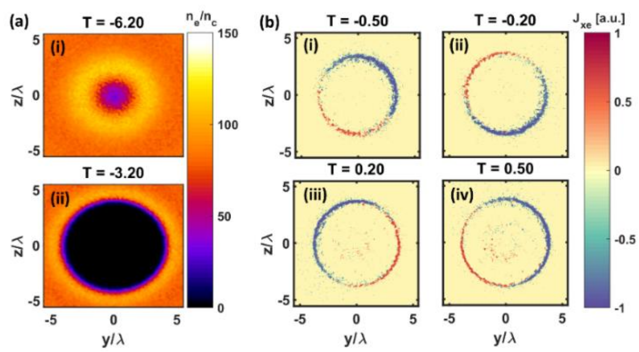

Figure 2. (Left panel) Electron density in the transverse plane at two different time snapshots. Here we see the onset of surface denting at earlier times and the creation of a plasma window at later times. (Right panel) Longitudinal electron current density at four different time snapshots over the course of a single laser cycle. For this normally incident circularly polarized laser, the rotating surface oscillations in the longitudinal direction are induced by the transverse laser field.

4. Conclusion

In conclusion, a circularly polarized laser normally incident on an ultrathin foil will generate harmonics in both the transmitted and reflected directions with each harmonic containing orbital angular momentum with a topological charge of (n-1) for the n^{th} harmonic. The emission of the helical phase fronts of the harmonic radiation can be understood by the transverse laser field inducing oscillating longitudinal currents that rotate in the transverse plane.

5. Acknowledgements and References

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