GENERATION OF OPTICAL ORBITAL ANGULAR MOMENTUM USING A SEEDED FREE ELECTRON LASER*

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Abstract

We propose an effective scheme for the generation of intense extreme-ultraviolet (XUV) light beams carrying orbital angular momentum (OAM). The light is produced by a high-gain harmonic-generation free-electron laser (HGHG FEL), seeded using a laser pulse with a transverse staircase-like phase pattern. The transverse phase modulation in the seed laser is obtained by putting a phase-mask in front of the focusing lens, before the modulator. The staircase-like phase pattern is effectively transferred onto the electron beam in the modulator and the microbunching structure is preserved after frequency up-conversion in the radiator. During light amplification in the radiator, diffraction and mode selection drive the radiation profile towards a dominant OAM mode at saturation. With a seed laser at 260 nm, gigawatt power levels are obtained at wavelengths approaching those of soft x-rays. Compared to other proposed schemes to generate OAM with FELs, our approach is robust, easier to implement, and can be integrated into already existing FEL facilities without extensive modifications of the machine layout.

INTRODUCTION

At present, the radiation modes of modern free-electron lasers (FELs) working at saturation are limited to a fundamental Gaussian-like mode with no azimuthal phase variation. This is true for FELs based on self-amplified spontaneous emission (SASE), where the amplification starts from electron shot-noise [1–6], as well as for seeded FELs, such as those based on high-gain harmonic-generation (HGHG), where the amplification process is triggered by a coherent input seed [7–9].

Generation of high-order radiation modes, however, is a subject of strong interest, not only from the fundamental point of view but also in practical applications. In particular, helically phased light beams or optical vortices with a field dependence of $\exp(il\phi)$, where ϕ is the azimuthal coordinate and l an integer referred to as the topological charge, are currently among intensively studied topics in optics. These light beams, which carry orbital angular momentum (OAM) [10] that can be transferred to atoms, molecules, and nanostructures [11–16], have already been utilized at visible and infrared wavelengths in a wide variety of applications, ranging from micromanipulation [17], detection of spinning objects [18], microscopy [19], and optical data transmission [20–22]. Perhaps the most promising applications of vortex beams at short wavelengths are in x-ray magnetic circular dichroism, where different OAM states allow the separation of quadrupolar and dipolar transitions [23], photoionization experiments, where the dipolar selection rules are violated giving rise to new phenomena beyond the standard effect [24], and in resonant inelastic x-ray scattering, where vortex-beam-mediated coupling to vibrational degrees of freedom could provide important information on a wide range of molecular materials [25].

Hemsing and coworkers proposed two clever approaches to generate intense vortex beams at short wavelengths using FELs. The first one exploits the interaction of an electron beam (e-beam) with a seed laser in a helical undulator [26], while the second one is based on the echo-enabled harmonic generation (EEHG) scheme [27], where two seed lasers and two magnetic chicanes are used to produce harmonic microbunching of an e-beam with a corkscrew distribution [28]. A proof-of-principle experiment has recently been performed to demonstrate the first scheme using a single undulator section, generating optical vortices at 800 nm [29] . In this approach, however, OAM beams are produced at the fundamental frequency of the seed. Reaching short wavelengths would therefore require a coherent XUV or x-ray input signal, which is not trivial to obtain. On the other hand, the technique based on EEHG uses a relatively complex setup, which has yet to be thoroughly tested in experiments.

THE SCHEME TO GENERATE OAM WITH A SEEDED FEL

The scheme is shown in Fig. 1. The main difference with respect to the standard HGHG setup [30] is the use of an optical phase mask in order to create a transverse phase modulation in the seed laser profile. Naively, the simplest way to produce an XUV/x-ray optical vortex with this setup would be to seed the FEL directly with an OAM beam, by using a spiral phase plate as the phase mask. However, this approach fails at short wavelengths. The reason is that the topological charge l_n of higher harmonics is multiplied with the harmonic number n [28]; i.e., $l_n = ln$, where l is the topological charge of the seed. This results in a high-order OAM mode at the entrance of the radiator, which is tuned to $\lambda = \lambda_s/n$, where λ_s is the seed laser wavelength. Due to a lower coupling with the e-beam and stronger diffraction, this high-order OAM mode is not amplified in the radiator [28], leading to a dominant fundamental (non-OAM) mode at saturation.

The idea behind our approach is the following: instead of a helical transverse phase profile, a four quadrant staircase-like phase structure is imprinted onto an axially symmetric e-

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beam in the modulator. The resulting transverse distribution of electrons in phase can be represented by the following matrix:

$$B_m = \begin{bmatrix} \frac{1}{2}\pi & 0 \\ \pi & \frac{3}{2}\pi \end{bmatrix}, \tag{1}$$

meaning simply that the electrons with the azimuthal coordinate between $-\pi/4$ and $\pi/4$ have a relative phase of 0, the electrons with $\pi/4 \leq \phi < 3\pi/4$ have a relative phase of $\pi/2$ and so on. Following frequency up-conversion at the radiator entrance, the phase distribution is multiplied by n, giving:

$$B_r = n \begin{bmatrix} \frac{1}{2}\pi & 0 \\ \pi & \frac{3}{2}\pi \end{bmatrix} \quad \mathrm{mod}\ 2\pi, \tag{2}$$

which for odd $n = 2k + 1$, where k is an integer, becomes:

$$B_r = \begin{cases} \begin{bmatrix} \frac{1}{2}\pi & 0 \\ \pi & \frac{3}{2}\pi \end{bmatrix} = B_m, & \text{for even } k \\ \begin{bmatrix} \frac{3}{2}\pi & 0 \\ \pi & \frac{1}{2}\pi \end{bmatrix}, & \text{for odd } k. \end{cases} \tag{3}$$

The above equations show that the transverse microbunching structure is preserved for odd harmonics even after frequency up-conversion. The odd harmonics therefore carry the same staircase-like transverse phase pattern, which determines the spatial properties of the radiation at the radiator entrance. Because this initial bunching distribution contains a strong helical component, the radiation profile evolves into a dominant $l = 1$ OAM mode at saturation. With an initial Gaussian transverse seed profile with $\lambda_s = 260$ nm and e-beam parameters corresponding to modern seeded FELs, optical beams carrying orbital angular momentum at XUV wavelengths and gigawatt power levels can be generated.

The interested reader can find more details about the generation scheme together with numerical results using the parameters of modern generation FELs in PRL 112, 203602 (2014).

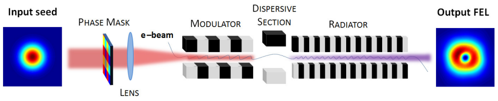

Figure 1: The scheme to generate XUV OAM beams using a HGHG free-electron laser.

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