Physics

VIEWPOINT

Free-Electron Laser Does the Twist

Researchers have used a free-electron laser to produce vortex radiation at extreme-ultraviolet wavelengths.

by Gregory Penn*

Light is perhaps the pre-eminent scientific tool, not just for observing objects but also for manipulating them. Near the visible part of the spectrum, conventional laser light is especially important thanks to its coherence and tunability, which give scientists fine control of the light beam in space and frequency. But conventional lasers do not operate in the extreme ultraviolet (XUV) wavelength band, usually defined as the range 10–100 nm, let alone at shorter wavelengths. Going beyond the ultraviolet would allow, for example, better imaging resolution to be obtained. One means of generating XUV radiation is the free-electron laser (FEL). FELs provide short-wavelength versions of many of the capabilities of conventional lasers, including coherence, polarization control, ultrashort pulse durations, and high intensities. In a new study, Primož Rebernik Ribič at the Elettra Sincrotrone Trieste research center in Italy and colleagues [1] have carried a different laser capability—vortex radiation [2]—over to XUV wavelengths for the first time with a FEL.

Vortex radiation can be described as an orbital angular momentum mode or an electromagnetic vortex, among other names. In conventional electromagnetic radiation, electric and magnetic fields may rotate uniformly in a clockwise or counterclockwise sense with respect to the direction of light propagation, giving the radiation right- or left-hand circular polarization. By contrast, in vortex radiation the fields rotate around a dark spot (called a zero point or phase singularity) in a helical fashion (Fig. 1). An electromagnetic vortex is characterized by an integer angular momentum l, where $l = 0$ has no vortex and no singularity, $|l| = 1$ corresponds to corkscrew-like fields, $|l| = 2$ to double-helix configurations, and so on.

Rebernik Ribič and colleagues' experiment has its roots in the growing interest in vortex radiation at visible wavelengths as a tool for measurement and manipulation of matter, and it improves on an earlier FEL experiment that produced vortices in the infrared [3]. Vortex radiation in the XUV has also been produced recently using a laser hitting a gas jet [4]. In this case, the frequency of an intense laser is converted to higher, XUV frequencies through a nonlinear process known as high-harmonic generation (HHG). This HHG source, as well as similar sources that use other objects such as metal foils as targets, is compact and accessible to a small laser lab. But these sources only work in or close to the XUV range, and they are very limited in their radiation power at short wavelengths.

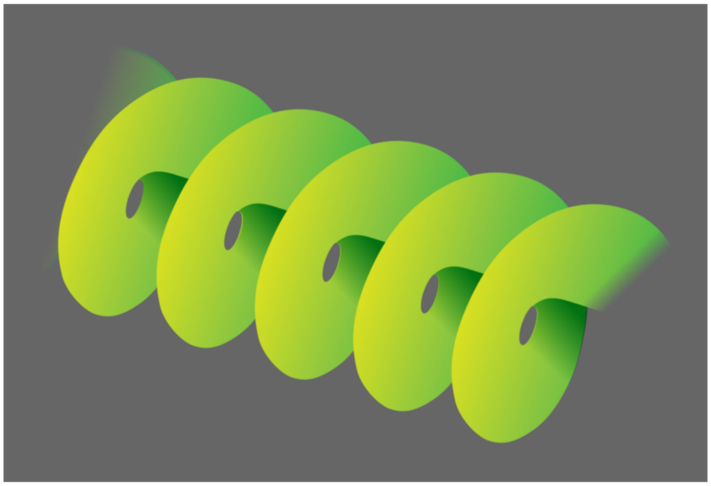

Figure 1: In an optical vortex mode [2], the electric and magnetic fields rotate around a dark spot in a spiral manner. (APS/Alan Stonebraker)

By contrast, FELs—which shake a high-energy electron beam, causing it to radiate like an antenna and amplify the radiation like a laser—can yield high power and extremely small wavelengths, even x rays. However, FELs require a large-scale particle accelerator to produce the high-quality and high-energy electron beams. Currently, FELs form the basis of over a dozen experimental facilities around the world, and there are more facilities planned. Overall, HHG- and FEL-based approaches are complementary; different experiments would be done at FEL facilities, which offer limited and costly experimental time, than at laser labs, which have a lower cost of entry. For example, FEL facilities can combine multiple sources of radiation in a single experiment or provide enough power to rapidly record moving images.

Electromagnetic vortices can appear as a part of many

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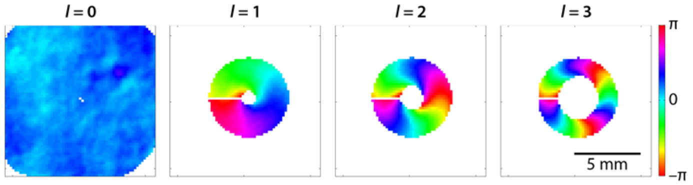

Figure 2: Rebernik Ribič and colleagues [1] have generated vortex modes at extreme-ultraviolet wavelengths with a free-electron laser. The measured laser phase for the $l = 0$ mode shows a uniform phase, corresponding to a normal laser spot. The higher-l modes have a central region with no laser power and an annular spot around which the phase varies by $2\pi l$ radians. (P. Rebernik Ribič *et al.*, Phys. Rev. Lett. (2017))

common radiation sources, but they are usually mixed together such that the overall orbital angular momentum averages out, much like unpolarized light is really a mix of different polarizations. To make full use of vortices, one must be able to produce a single mode in one pulse and, preferably, be able to switch back and forth between different modes, including the $l = 0$ mode. Observing differences in how the different modes interact with an object allows sensitive measurements of otherwise hidden material properties. Molecules or materials with magnetic properties, or whose properties change when exposed to electromagnetic fields, are especially interesting subjects of experiments using vortices. Vortices can apply a torque to specific constituents in a sample or be used to detect either geometric structures (such as chirality) or internal degrees of freedom (such as spin). Because a vortex has an isolated zero point, it can also be used for high-resolution imaging beyond the diffraction limit through so-called stimulated emission depletion microscopy [5]. In this technique, a fluorescent molecule is driven to a nonfluorescent state by appropriately chosen laser light. Only molecules very close to a zero point of the laser can then fluoresce. And instead of forming an image of the sample all at once, as in conventional microscopy, a scan is performed over pixels, and these pixels can be much smaller than the wavelength of the light itself.

In their new experiments, Rebernik Ribič and colleagues modified the FERMI light source—a FEL at the Elettra Sincrotrone Trieste—to generate XUV vortex modes (Fig. 2). They used two different techniques. The first involves a device known as a zone plate made from single-crystal silicon [6]. The plate modifies a FEL radiation pulse by adding a variable phase shift to the pulse as it propagates through a pattern etched into the zone plate. This is a general method that, with the help of spiral patterns or other structures, can be used to produce various vortex modes. The second technique exploits the fact that a FEL radiating at full power in a helical magnetic field will also radiate an $|l| = 1$ vortex mode at half of the dominant wavelength of the FEL. The team used a metallic crystal to selectively block the longer-wavelength radiation, revealing the weaker but still substantial vortex mode.

Both of these techniques promise to scale to sub-angstrom wavelengths and to achieve a peak power beyond a gigawatt. An important aspect of these schemes, shared with recent HHG experiments, is that high harmonics of conventional laser wavelengths can have low angular momentum numbers that are selectable and of high quality. Low angular momentum numbers are desirable because higher angular momentum states are delicate and easily break up into structures that have multiple phase singularities. The results promise to yield higher-resolution images than is currently possible and to improve our understanding of magnetic materials and of structures on the nanometer scale.

This research is published in *Physical Review X*.

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