optics & photonics focus

Twisted Electrons

Recent experiments lend a brand new twist to the tale unfolding in the field of electron microscopy. Promising electron vortices have made their appearance at the crossroads between nanotechnology and magnetism.

What can be qualified as *twisted*? A wire? Or a rope, perhaps? You can twist your ankle, painful as that may sound. Logic and sense of humor can also be twisted. The adjective twisted, in its literal or metaphorical sense, can be applied to qualify a range of concepts and objects in everyday life or, indeed, in a research lab. What about quantum particles like electrons? Can they be *twisted*? They literally can. This has been shown in a recent experiment where a beam of twisted electrons was generated by a hologram. The experiment was performed by Johan Verbeeck and He Tian at the University of Antwerp (Belgium), and Peter Schattschneider at the Vienna University of Technology (Austria).

Electrons are elementary particles, a little like photons; but what exactly does *twisted* mean when used to refer to electrons or, prior to that, to photons [1]? The photons of a laser beam, for example, normally travel along the direction of propagation with a constant phase, like a squad of soldiers all marching at the same pace. An optical vortex is a beam of light whose phase twists spirally along the direction of propagation of the beam [2]. Because of this spiral movement, the optical vortex looks like a doughnut: a ring of light with a dark hole in its center.

Electrons, like photons, can also be induced to twist along the direction of propagation. “The first demonstration of an electron vortex beam was given by Uchida and colleagues [3] by making use of an accidental stacking of thin graphite flakes that acted as a rough approximation to a spiral phase plate,” explains Verbeeck. “Our work shows that, by making use of a technique called *holographic reconstruction*, already in use with photons, a much more reproducible setup can be obtained. This method is based on a computer-designed hologram that encodes a complex wave function of choice. In this case, we chose a wave function with a helical wave-front structure.”

Holography works for light as a tape recorder works for sound: when recording, the original sound is encoded onto a tape so that it can be later reproduced in the absence of the original source of that sound. Similarly, the interference pattern between a reference beam and the light scattered by an object can be encoded in a hologram. The hologram can then be used to recreate the impression of the object when illuminated with the same reference beam used in encoding. More simply, somebody looking at the hologram will be able to see the object even when the object is no lon-

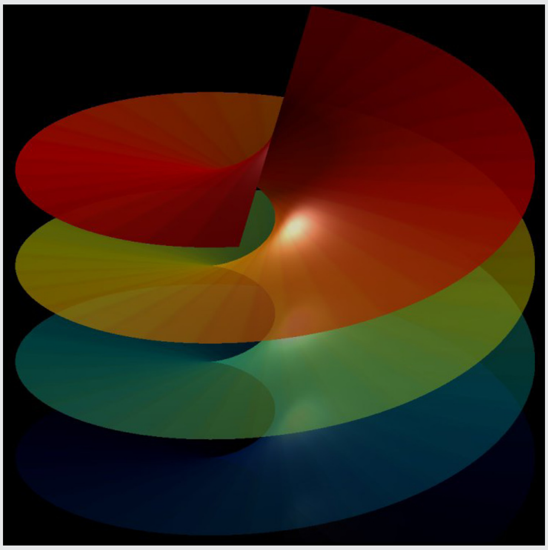

Figure 1: Twisting phase. The phase of an electron or optical vortex twists spirally around the direction of propagation of the beam. Because of this spiral movement, the light waves cancel each other out at the center of the beam, so that the optical vortex looks like a doughnut, a ring of light with a dark hole at its center.

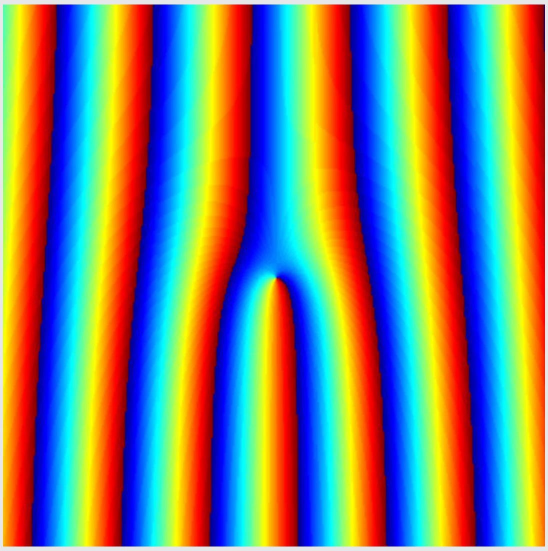

Figure 2: The pitch-fork hologram. The pitch-fork hologram, which has been traditionally used to generate optical vortices, can now also be used to generate electron vortices. The singular point at the centre is the main reason for the production of the vortex, and it also gives the hologram its name.

ger there. “Transferring this idea to electrons meant that we had to cut a mask with the computer-calculated hologram onto a thin foil of platinum (a few hundred nanometers in thickness),” Verbeeck points out. “This mask can now be reliably fabricated in a matter of hours and placed inside any existing transmission electron microscope.”

Electron vortices are likely to help expand the range of applications of electron microscopy. Since its invention in 1931, this field has made giant leaps forward and it is nowadays widely used in research and industrial labs for many applications, such as imaging, spectroscopy or lithography, where a high resolution of a few nanometers is essential. “The field in which electron vortices will be most useful is that of electron spectroscopy,” says Verbeeck. “We have demonstrated that, when using electron vortex beams instead of conventional plane waves, we get a different spectrum in electron energy spectroscopy for ferromagnetic materials. These electron vortices, therefore, can be a very useful tool in determining magnetism in materials on the atomic scale.”

Etienne Snoeck at the Centre d’Elaboration de Matériaux et d’Etudes Structurales in Toulouse (France) points out that, although “there will not be any immediate industrial application for such electron vortices, […] as the development of microelectronic devices in the nanometer range has already benefited from the capability of performing local structural and chemical measurements by transmission electron microscopy, these new results will allow us to perform magnetic measurements at a local scale that will help develop new magnetic devices.” To quote Verbeeck, “this is a crucial step in the development of new devices where nanotechnology and magnetism combine.”

[1] G. Molina-Terriza, J. P. Torres & L. Torner, *Twisted Photons*, Nat. Phys. **3**, 305-310 (2007).

[2] S. Cherukulappurath, *Tiny Plasmonic Whirpools*, Opt. Photon. Focus **8**, 7 (2010).

[3] M. Uchida & A. Tonomura, *Generation of Electron Beams Carrying Orbital Angular Momentum*, Nature **464** 737-739 (2010).

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J. Verbeeck, H. Tian & P. Schattschneider, **Production and application of electron vortex beams**, Nature (2010) **467**, 301-304.