Tying the knot with computer-generated holograms: Winding optical path moves matter

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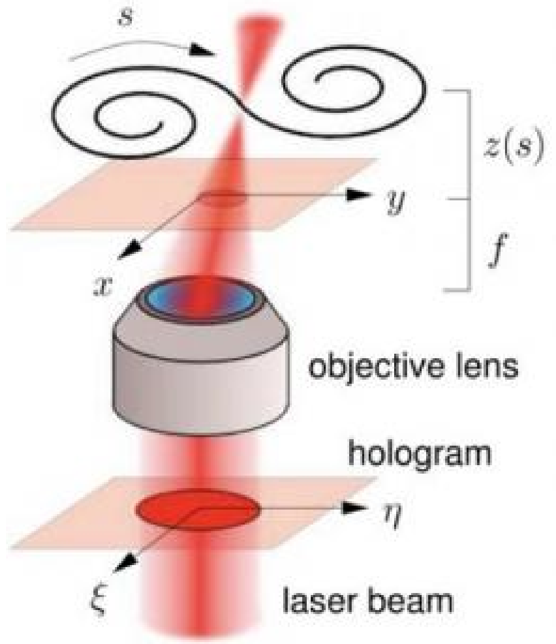

A laser beam is imprinted with a hologram in the input pupil of an objective lens. The hologram is projected through the objective's focal plane and comes to a focus along a 3-D curve parameterized by its arc length, s. Credit: Optics Express

In the latest twist on optical knots, New York University physicists have discovered a new method to create extended and knotted optical traps in three dimensions. This method, which the NYU scientists describe in the

Optical Society's open-access journal *Optics Express*, produces "bright" knots, where the maximum of the light intensity traces out a knotted trajectory in space, for the first time allowing microscopic objects to be trapped along the path of the knot. The method may even, one day, help enable fusion energy as a practical power source, according to the NYU team.

Optical traps can be used to confine and manipulate small objects—ranging in size from a few nanometers to several hundred micrometers—in 3-D. They work because variations in the intensity of the light produce forces that push small objects toward bright regions. The trapping of small objects is widely used for a broad range of research applications in biophysics, condensed matter physics and medical diagnostics.

Ordinary optical traps use Gaussian laser beams that focus to a spot. The beams being used to create extended optical traps focus instead to curves, much like the bright patterns on the bottom of swimming pools. And these bright curves can be tied in knots.

Knotted traps are made by imprinting a computer-generated hologram on the wavefronts of an otherwise ordinary beam of light. NYU undergraduate student Elisabeth Shanblatt and NYU physicist David Grier, the authors of the Optics Express paper, use a "liquid-crystal spatial light modulator" to project their holograms. This is essentially the first cousin of a conventional LCD television screen. The spatial light modulator imprints a calculated pattern of phase shifts onto the light. When the modified beam is brought to a focus with a high-power lens, the region of maximum intensity takes the form of a 3-D curve. This curve can cross over and through itself to trace out a knot. Moreover, the same hologram can redirect the light's radiation pressure to have a component along the curve, so that the total optical force "threads the knot."

When Shanblatt and Grier began this investigation, they thought that creating knots would be a compelling and aesthetically pleasing demonstration of their method's power. Once the knots actually worked, they realized that there are very few—if any—other practical ways to create knotted force fields. Previously reported knotted vortex fields have intensity minima along the knot, rather than the intensity maxima, or "bright knots" that can be created using the computer-generated holograms.

Shanblatt was working on a project with Grier investigating these holographic optical traps, when they discovered a method for projecting holographic optical traps along arbitrary curves in 3-D, with amplitude and phase profiles independently specified (See figure above).

"The knotted optical force fields we created use intensity gradients to hold microscopic objects in place and phase gradients to thread them through the knot," says Shanblatt, describing their method. "These optical knots are a special type of a very general class of 3-D optical traps that can be created using holographic techniques."

Ordinary optical traps have current applications in biophysics, where they are used as surgical tools and to probe the elastic properties of biomolecules, and in condensed matter physics, where they assemble nanomaterials into 3-D functional structures and gauge the forces between microscopic objects. Extended optical traps are especially handy in moving small objects such as biological cells through microfluidic lab-on-a-chip devices. And they can be used to measure very small interactions among such objects, which is helpful for medical diagnostic tests.

Perhaps the most exciting and futuristic potential application the NYU team sees for their method is to create knotted current loops of charged particles in high-temperature plasmas. This is a long-sought-after goal for developing fusion energy as a practical power source.

How can their knots of light solve problems of fusion energy? Fusion reactors work by slamming light atomic nuclei into each other so hard that the nuclei fuse into heavier elements, releasing lots of energy. The best way to accomplish this, Grier says, is to heat the atoms to a high enough temperature so that they can overcome all of the barriers to fusion. At these temperatures, the atoms' electrons ionize and the gas becomes a plasma.

This is doubly good, notes Grier, because you can pass large electric currents through the plasma, therefore heating it still more. "You can also act on the currents with magnetic fields to contain the hot plasma, preventing it from destroying its physical container. These fusion plasmas are literally as hot as the core of the sun," he adds.

A problem occurs when currents flowing through plasma in a fusion reactor become unstable; this is similar to what occurs when the currents flowing through the plasma in a neon sign flicker. The currents thrash around, cool the plasma, damage the container, and generally prevent the process from generating useful energy.

"If the currents in a plasma are tied into a knot, the knot can eliminate most, if not all, of these instabilities because the magnetic field lines generated by the knotted current can't pass though each other," explains Grier.

Shanblatt and Grier believe that projecting a knotted optical force field into a plasma might prove to be a good way to initiate a knotted current loop. If so, the knotted current could then be ramped up by other conventional means. The result? Perhaps, a stable, high-temperature plasma capable of producing bountiful fusion energy.

More information: "Extended and Knotted Optical Traps in Three Dimensions," Elisabeth R. Shanblatt, David G. Grier, Optics Express, Vol. 19, Issue 7, pp. 5833-5838, www.opticsinfobase.org/oe/abst … cfm?uri=oe-19-7-5833

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