"Twisted" light beams promise an optical revolution

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Some of history's most brilliant researchers have studied the nature of light over the centuries, from Newton to Maxwell to Einstein. And yet it continues to surprise. Indeed, one discovery about light's peculiar behavior offers new insights into how light works while suggesting some intriguing applications.

In 1992, physicists mastered a surprising feat—generating light beams that twist like a helical corkscrew (1). "It's a very good reminder how you can still find new things in something we all thought we knew very well," says engineer Siyuan Yu of the University of Bristol in the United Kingdom.

This phenomenon is called twisted light and has led to a new field of optics. Today twisted light is being used to build optical tweezers and ultra-powerful microscopes, and it could eventually be used in microscale machinery and for novel spectroscopic analyses. But perhaps its most important use is in optical communications, where it has the potential to greatly enhance the bandwidth of data networks.

Light, Reimagined

Light is an electromagnetic wave, comprised of electric and magnetic fields. The fields oscillate in a direction perpendicular to the direction in which the wave is moving. If the electric field is always oscillating in the same plane, the light is said to be linearly polarized. Photons of such light have linear momentum. If

In 2016 researchers used laser light with optical orbital momentum to beam a message a record 143 kilometers between the Canary Islands of La Palma and Tenerife. Image courtesy of Mario Krenn (University of Vienna, Vienna).

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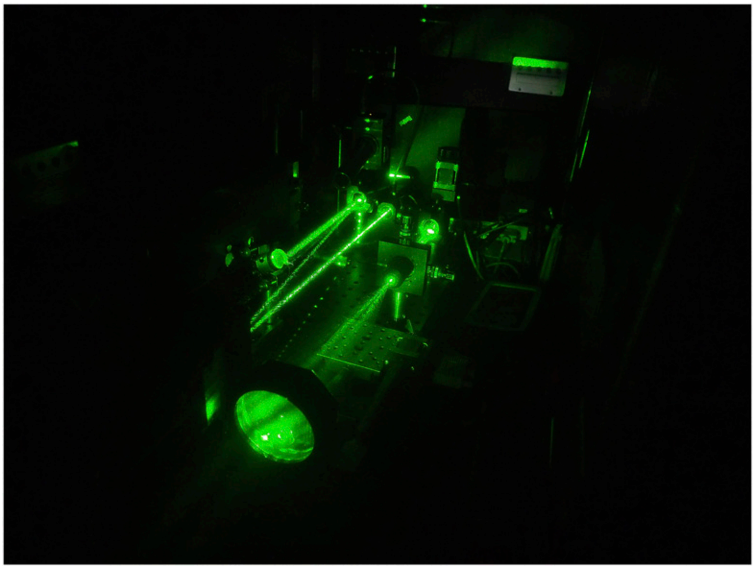

Despite turbulent atmospheric conditions, researchers used this laser apparatus to send the message "Hello World" a long distance, demonstrating the utility of light with OAM. Image courtesy of Mehul Malik (Institute for Quantum Optics and Quantum Information Vienna, Vienna) and Mario Krenn (University of Vienna, Vienna).

photons from stars fell on a solar sail made of some diaphanous material, for example, the sail would absorb the photons' momentum and help propel a spacecraft.

And if the direction of the plane in which the light's electric field is vibrating is itself rotating as the wave moves, light is said to be circularly polarized. Light, in this case, has spin angular momentum. A floating bead hit with such light will spin like a planet rotating on its axis.

It turns out that this is not the only way light behaves. If you take a cross-section of the wave, perpendicular to the direction of travel, then this cross-section contains individual mini-waves, each of which is oscillating. Usually, all the mini-waves are in lockstep—they are in the same phase of their oscillations.

But the mini-waves can all be in different phases. So, within some cross-section, the location of a mini-wave with a given phase will keep changing, rotating around the center as the light passes by. Such light is said to have orbital angular momentum (OAM). Hit with this type of light, a free-floating bead will revolve in a circle around a central point like a planet orbiting a star.

Researchers have known since 1932 that light can have OAM, but it was thought to emerge only from unusual maneuvers of electrons as they spun around atomic nuclei (2). After the invention of the laser, engineers in the 1970s developed and studied "vortex beams" that had a column of light with a hole in the center (3). They didn't know it at the time, but these lasers carried OAM.

Then, in 1991, physicist Robert Spreeuw, at the time a PhD student in Han Woerdman's lab at Leiden University in The Netherlands, sat down during a team coffee break and presented some ideas about how to make twisted light. "The first reactions were a bit skeptical," Spreeuw recalls. "But we kept thinking about it and, bit by bit, it started to look more realistic."

In 1992, Woerdman and his colleague Les Allen created twisted light in the lab and showed that even a single photon of light has OAM. The next year they showed how to convert a normal helium–neon laser to one that carried OAM (4).

One way to create twisted light is to send it through a seashell-like lens, which shapes the oscillations of the electric field into a form resembling a helix. It's as if you took a rod and swirled it around to create a vortex in the phases of the electromagnetic waves, explains physicist Dmitry Pushin at the University of Waterloo in Canada.

Although some of these techniques are still in the lab, engineers are excited about the potential uses. "Right now we're in the exploration era," says electrical engineer Alan Willner of the University of Southern California in Los Angeles. "But with such a unique type of a beam, it's hard to imagine that these things won't have a huge impact in some areas."

Gaining Momentum

Preliminary finds have suggested some uses in the last 25 years. In 1995, an Australian team placed small particles in the dark, central cavity of an OAM laser and watched them whirl around, providing visual proof that the light was carrying OAM (5). The researchers could even reverse the direction of the OAM laser's twist and spin the particles the opposite way.

Twisted light beams have since been used to build optical tweezers, which use laser light to trap microscopic particles and control their movements. Instead of merely pushing or pulling at the particles, an OAM laser works like a tiny wrench that can torque objects around. In recent years, engineers have built ever-smaller OAM beams—some barely as wide as a human blood cell—in the hopes of using them to drive microscale gears and even nanotech machinery (6). Biomedical diagnostic devices built on a single silicon chip could use such twisted light to operate microscopic equipment or detect the flow and viscosity of minuscule amounts of liquids.

Because twisted light is so unusual, it can excite atoms and molecules into odd states not often seen in nature. Electrical engineer Natalia Litchinitser of the University at Buffalo in New York and her colleagues have used metamaterials—synthetic composites that exhibit properties not found in natural materials—to squeeze an OAM beam so that it is only a few nanometers wide. Using such beams, they hope to stimulate atoms and molecules into energy states that are extremely difficult to achieve naturally (7). When the molecules fall back to their ground states, they release characteristic flashes of light, which Litchinitser says could be useful in new kinds of spectroscopic analysis, for instance teasing out the individual components of complex compounds.

But perhaps the biggest application of twisted light is communications. So far, researchers have been increasing the data rate of communication links by manipulating the color, intensity, or polarization of light. "We've packed as much information into all the degrees of freedom that we have at the moment of the light," says physicist Andrew Forbes of the University of Witwatersrand in Johannesburg, South Africa. "The only thing left is the pattern of the light."

Enter twisted light. A single beam can have multiple modes, containing light with, for example, one, two, three, or potentially an infinite number of twists. These helices are each distinct from one another, so they can each be encoded with information, sandwiched together, and sent to a distant receiver. Even a single photon, when twisted appropriately, can encode numerous bits of information.

Physicist Miles Padgett of the University of Glasgow in Scotland and his colleagues kicked off this discipline in 2004 using a holographic pattern to split an OAM laser into nine separate spirals and sending them 15 meters through the air to a receiving telescope, which was able to distinguish and read out all the modes simultaneously (8).

The bandwidth of this early demonstration wasn't particularly high. "It could be outperformed by a man with a flag," Padgett says. Then, in 2012, Willner led a team that sent 32 OAM modes through 1 meter of free space, giving it a data rate of nearly 2.5 terabits per second (9).

Latest Twist

But if OAM beams are to be used for communications, they will have to travel farther. In 2014, a team in Vienna set a record by using twisted light to send pixelated images of famous Austrians—Wolfgang Mozart, Erwin Schrodinger, and Ludwig Boltzmann—between two sites in Vienna separated by 3 kilometers (10). The team used beams with four twists, allowing them to transfer data at a sluggish four pixels per second. Two years later the same team upped their own record by beaming the message "Hello World!" between two mountains in the Canary Islands separated by 143 kilometers (11). The next challenge will be to send twisted light through optical fibers.

Recently, physicists have shown that photons are not the only ones with OAM. Dmitry Pushin and his colleagues have demonstrated that neutrons, which according to quantum mechanics act as both particles and waves, can be converted to possess OAM modes (12). An OAM neutron beam could be a superior probe of certain materials than X-rays.

Even acoustic waves have been induced into OAM modes, allowing them to carry more information. Some researchers have suggested using OAM sound waves for underwater communication networks, because they travel well in water, whereas light is quickly absorbed (13).

The growing potential of OAM beams has astounded those who work with them and surprised those who first imagined their possibility. "At the time it was just a fun idea," says Spreeuw, who now works in an unrelated field. "I could never suspect it would grow into such an industry."

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