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Twisted Light in Optical Fiber

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Abstract

The demand for high data rate is burgeoning day by day. There is a need to increase the information carrying capacity of the conventional transmission system. Optical Fibers, which are one of the most popular transmission medium of data, can be used to carry twisted light. Twisted light stands for photons have a quantum characteristics called orbital angular momentum. Photons with OAM have electric and magnetic fields that corksrew rather than oscillate in a plane. There are theoretically infinite number of OAM values, and multiple beams having different orbital Angular momemtums can occupy the same fiber, allowing more data to be transferred.

1. Introduction

A new fiber-optic cable that seamlessly shuttles multiple beams of light simultaneously could drastically speed data transfer over the Internet. It's like having more fibers without actually laying more fibers. It can dispatch multiple beams of light through a single fiber. The idea goes back nearly four decades, but it's not an easy thing to do because traditional fibers allow light beams moving in parallel to interfere with each other, jumbling the 1s and 0s encoded in each beam. Recently, scientists have tried imparting twists into some of the beams so that they spiral along the fiber while others travel in a straight line, but that hasn't worked either.

A scientist Ramachandran and his team report building a 1.1-kilometer-long fiber that, for the first time, allows multiple beams to reach their destination intact. Their silica fiber is doped in places with other materials, which cause the beams to move at slightly different speeds and prevent them from mixing with each other. Using an instrument called a spatial light modulator to twist the beams, the researchers sent as many as four concurrent beams, transmitting data at speeds up to 1.6 trillion bits per second, through their custom fiber. They hope to squeeze more data into each of those beams using methods already exploited by the telecom industry. Ramachandran notes that the team manufactured its fiber at a commercial facility using standard methods, so if it were mass produced, the fiber should not cost much more than those now in use.

2. Angular Momentum of a Light

2.1 Orbital Angular Momentum

The orbital angular momentum of light (OAM) is the component of angular momentum of a light beam that is dependent on the field spatial distribution, and not on the polarization. It can be further split into an internal and an external OAM. The internal OAM is an origin-independent angular momentum of a light beam that can be associated with a helical or twisted wavefront. The external OAM is the origin-dependent angular momentum that can be obtained as cross product of the light beam position (center of the beam) and its total linear momentum.

A beam of light carries a linear momentum $\mathbf{P}$, and hence it can be also attributed an external angular momentum $\mathbf{L}_e = \mathbf{r} \times \mathbf{P}$. This external angular momentum depends on the choice of the origin of the coordinate system. If one chooses the origin at the beam axis and the beam is cylindrically symmetric (at least in its momentum distribution), the external angular momentum will vanish. The external angular momentum is a form of OAM, because it is unrelated to polarization and depends on the spatial distribution of the optical field. A more interesting example of OAM is the internal OAM appearing when a paraxial light beam is in a so-called "*helical mode*". Helical modes of the electromagnetic field are characterized by a wave front that is shaped as a helix, with an optical vortex in the center, at the beam axis (see figure). The helical modes are characterized by an integer number m, positive or negative. If $m = 0$, the mode is not helical and the wave fronts are multiple disconnected surfaces, for example, a sequence of parallel planes (from which the name "plane wave"). If $m = \pm 1$, the handedness determined by the sign of m, the wave front is shaped as a single helical surface, with a step length equal to the wavelength λ. If $|m| \geqslant 2$, the wavefront is composed of $|m|$ distinct but intertwined helices, with the step length of each helix surface equal to $|m|\lambda$, and a handedness given by the sign of m. The integer m is also the so-called "*topological charge*" of the optical vortex. Light beams that are in a helical mode carry nonzero OAM.

A careful analytic treatment of the electromagnetic field gives the total angular momentum of any light field in terms of a spin and orbital contibutions. In free space, the Poynting vector, which gives the direction and magnitude of the momentum flow, is simply the vector product of the electric and magnetic field intensities. For helical phase fronts, the Poynting vector has an azimuthal component, as shown in figure 1. That component produces an orbital angular momentum parallel to the beam axis. Because the momentum circulates about the beam axis, such beams are said to contain an optical vortex.

The most common form of helically phased beam is the so-called Laguerre–Gaussian (LG) laser mode. In general, lasers emit a beam that gradually expands as it propa- gates. The magnitude and phase of the electric field at dif- ferent positions in the cross section are described by a mode function. For most laser beams without helical phas- ing, that function is the product of a Hermite polynomial and a Gaussian. Hermite–Gaussian (HG) modes have sev- eral intensity maxima, depending on the order of the poly- nomials, arrayed in a rectilinear pattern and separated by intensity zeros. Laguerre- gaussian light beam possess an OAM of I hbar (i.e. I h/(2 pi)) per photon, where I is the azimuthal index of the beam. these beams are examples of light beams with an intensity structure that is symmetric about the beam's axis and a phase structure of I intertwined phase fronts. there are mechanical effects in such beams: when microscopic particles absorb such light, they begin to rotate (conservation of angular momentum).

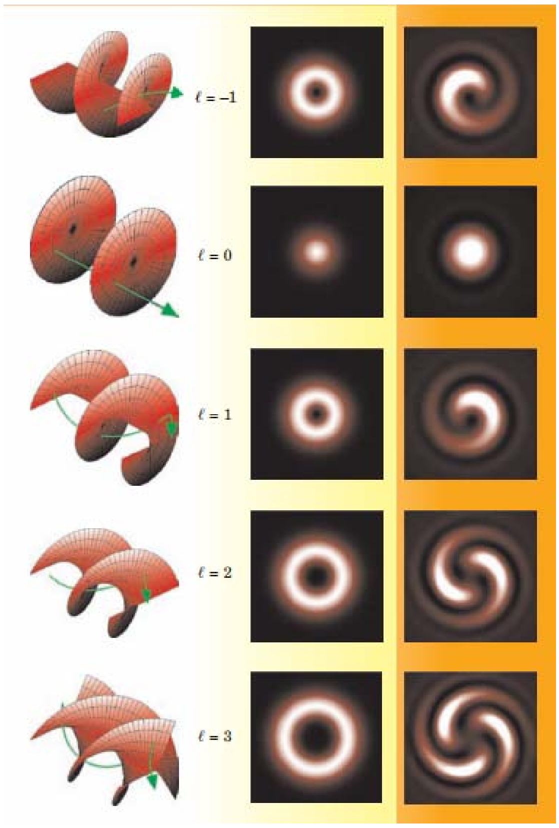

Figure 1

2.2 Spin Angular Momentum

The spin angular momentum of light (SAM) is the component of angular momentum of a light beam that can be associated with its circular or elliptical polarization. An electromagnetic wave is said to have circular polarization when its electric and magnetic fields rotate continuously around the beam axis during the propagation. The circular polarization is left (L) or right (R) depending on the field rotation direction (but be careful that both conventions are used in science, depending on the subfield). When a light beam is circularly polarized, each of its photons carries a spin angular momentum of $\pm\hbar$, where $\hbar$ is the reduced and the $\pm$ sign is positive for **Left** and negative for **Right** circular polarizations (this is adopting the convention most commonly used in optics). This SAM is directed along the beam axis (parallel if positive, anti parallel if negative).

2.3 Total EM field Angular Momentum

Electromagnetic (EM) beams do not only carry energy, power (Poynting flux, linear momentum), and spin angular momentum (SAM, wave polarization), but also orbital angular momentum (OAM).

The total angular momentum J^{EM} can be separated into two parts

$$\mathbf{J}^{\mathrm{EM}} = \frac{\varepsilon_0}{2i\omega}\left\{\int \mathbf{E}^* \times \mathbf{E}\ \mathrm{d}^3x + \int \sum \mathbf{E}_i^* \left(\left[(\mathbf{x}-\mathbf{x_0})\times\nabla\right]\right)\mathbf{E}_i \hat{\mathbf{e}}_i\right\} \mathrm{d}^3x$$

- The first part is the spin angular momentum (SAM) S^{EM}, a.k.a. wave Polarization,
- The second part is the orbital angular momentum (OAM) L^{EM}.

In general, both linear momentum P^{EM}, and angular momentum $J^{EM} = S^{EM} + L^{EM}$ are radiated all the way out to the far zone.

2.3 Difference between SAM and OAM

- SAM is tied to the helicity (polarization) of the light beam and for a single photon its value is:
  $Sz = \pm (h/2\pi)$
- OAM is tied to the spatial structure of the wavefront: the orbital terms are generated by the gradient of the phase; it determines the helicoidal shape of the wave front; for a single photon it assumes the value :
  $Lz = l\,(h/2\pi)$

with $l = 0$ for a plane wave with $S \parallel k$, and $l \neq 0$ for a helicoidal wave front because S precesses around k.

Polarization enables only two photon spin states, but actually photons can exhibit multiple OAM eigenstates, allowing single photons to encode much more information.

2.4 The Phenomenology of Orbital Angular Momentum

Simple comparisons of the behavior of spin and orbital angular momentum in Different situations prove to be a fruitful way to demonstrate their properties. First, However, we need to distinguish the general structures of light emitted by a laser And also its properties when converted to, for instance, an LG beam. Laser beams usually have spherical wavefronts while the azimuthal phase leads to beams with l intertwined helical wave fronts(Figure 2).

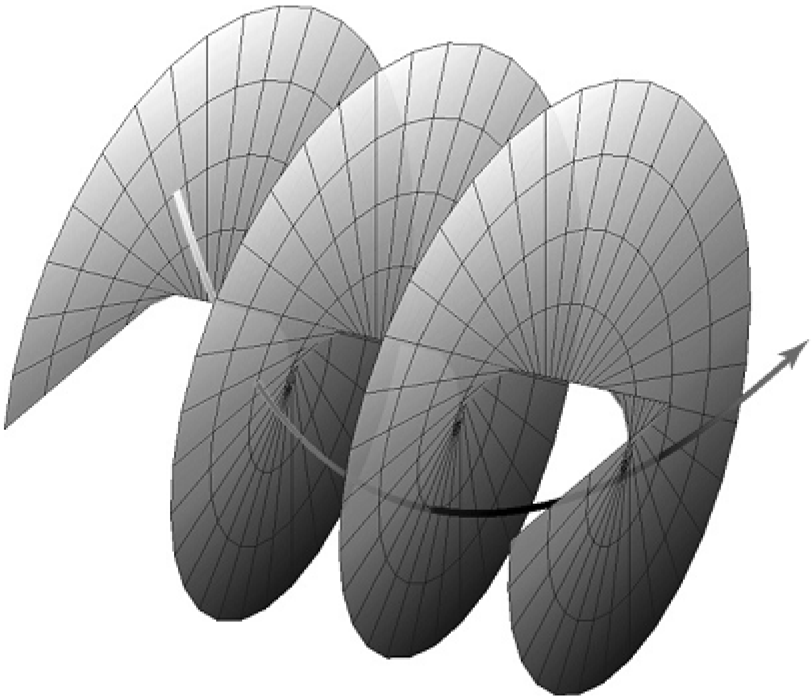

Figure 2

The LG beam is not the only example of a helical wavefront; Bessel beams ,Mathieu beams ,and Ince –Gaussian beams can also carry orbital angular momentum. In all cases ,the interference of these helical wavefronts with a plane wave gives rise to characteristic spiral interference fringes. The production of a pure, high-order LG mode from a laser beam was first achieved using a mode convertor based on cylindrical lenses . Prior to the Generation of LG beams with lenses, similar beams containing the same azimuthal Phase term had also been produced using diffractive optical elements Despite the various approaches that have been developed to generate helically Phased beams, they are not a feature unique to advanced optical experiment. Interference between two plane waves yields sinusoidal fringes. Interference Between three or more plane waves leads to points within the field cross Section of perfect destructive interference around which the phase advances or Retards by 2π. Nowhere is this more apparent than when examining the optical Speckle resulting from laser light being scattered from a rough surface, where each Black speck is a perfect phase singularity. In order to generate pure LG modes, the cylindrical lens mode converter remains a convenient approach.

3. Twisted Light

The principle behind the twisted-light concept was to bundle more information in a single beam of light which itself was a composite of other beams “twisted” or “corkscrewed” together. The twisted-light method proved to be promising, and in the latest development of the technology, researchers have shown that twisted light can be used in optical fibers, showing that the technology can be used practically.

Twisted light is able to carry far more information than regular light because it is able to encode more data within a single beam by using twists within the light itself to carry more information. Light has two kinds of momentum, spin angular momentum and orbital angular momentum. Using the latter, twisted light packs more data into the light by packaging this within the light’s varying degrees of twists.

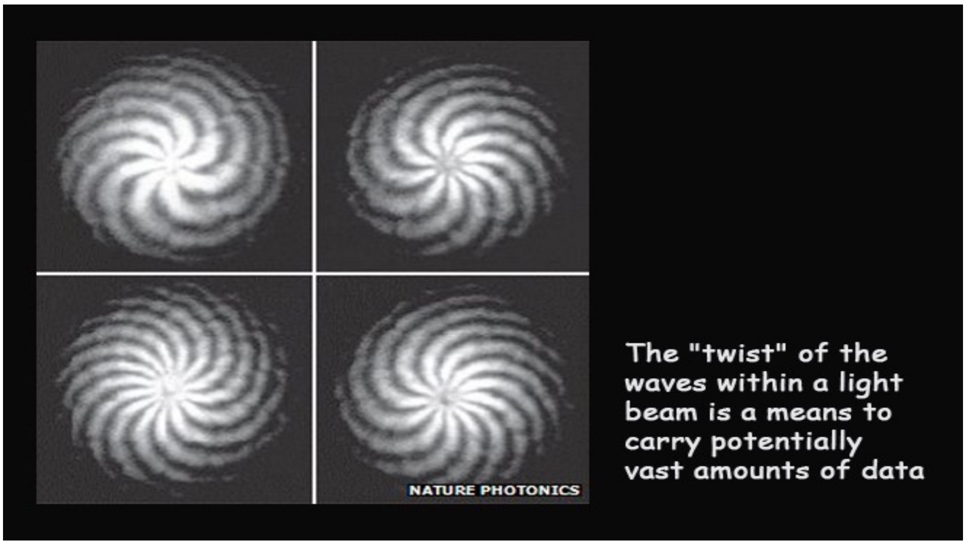

Figure 3

A new kind of optic fibre that can carry “twisted light” could provide internet speeds of over a terabit a second. The technology relies on donut-shaped laser light beams called optical vortices, or orbital angular momentum (OAM) beams, in which the light twists like a tornado as it moves along the beam path rather than in a straight line. Optical vortices were previously thought to be unstable in optical fibre, but Boston University (BU) Engineering Professor Siddharth Ramachandran has now designed a fibre capable of propagate them.

4. Working

Telecommunications companies use light to encode and send data through fiber-optic cables. Over the last few decades, scientists have increased bandwidth by enabling a single beam to carry more information, but their progress soon will be outpaced by the vast amounts of data people exchange. Laying more fibers would be expensive. The solution is to dispatch multiple beams of light through a single fiber. The idea goes back nearly four decades, but it's not an easy thing to do because traditional fibers allow light beams moving in parallel to interfere with each other, jumbling the 1s and 0s encoded in each beam.

Recently, scientists have tried imparting twists into some of the beams so that they spiral along the fiber while others travel in a straight line, but that hasn't worked either. Resigned to this light mixing, some researchers have created complex algorithms that decipher the amalgamated beams at the end of the cable, but the algorithms are slow and not 100 percent effective. In the June 28 Science, scientists report building a 1.1-kilometer-long fiber that, for the first time, allows multiple beams to reach their destination intact. Their silica fiber is doped in places with other materials, which cause the beams to move at slightly different speeds and prevent them from mixing with each other. Using an instrument called a spatial light modulator to twist the beams, the researchers sent as many as four concurrent beams, transmitting data at speeds up to 1.6 trillion bits per second, through their custom fiber. They hope to squeeze more data into each of those beams using methods already exploited by the telecom industry. fibers where manufactured at a commercial facility using standard methods, so if it were mass produced, the fiber should not cost much more than those now in use.

Twist in the beam is imparted due to a property known as "orbital angular momentum." A beam of light that carries digital data can twist in a helix as it moves through space.

The fascinating thing is that there can be many different rates of twisting for a beam. This property allows us to combine many data-carrying beams of differently twisted light. These beams actually occupy the same space but can be efficiently separated at a receiver. By doing so, we can increase the data capacity that is occupying the same space.

Recently, we transmitted data over open space in a lab at a rate of up to 2.5 terabits per second using multiple beams of light that were each twisted into a different helix. Each beam acted as an independent data stream – much like separate channels on your radio. To put that in layman's terms, the broadband cable that you probably use to check your email supports up to about 30 megabits per second. Our twisted-light system transmits more than 85,000 times as much data per second.

5. Application

Before long, this research, which was funded by the Defense Advance Research Projects Agency (DARPA) as a part of the InPho (Information in a Photon) program, will find its way into a variety of applications, both in space and on Earth. In the future, this will likely require a more cost-effective and integrated approach. At least in the near term, the technology's potential applications for terrestrial communications are limited, since it requires a clear line of sight and no turbulence or other interference.

Even on a clear day, the turbulent atmosphere will distort the phase front of the light wave. It is a bad idea to rely on phase manipulations for unguided atmospheric transmissions. It may be better to be used in vacuum. Because of atmospheric issues, therefore, the process might be more practical in satellite and space communications than on Earth, since space has no turbulence

This work can find various applications where large amounts of data must be exchanged between two points and OAM multiplexing is technically and economically advantageou. Turbulence may hurt performance of such optical wireless links, which means that longer-range applications can succeed in space. Just as promising is the possibility that OAM processes could be adapted to fiber optic cables, which are the basis of the Internet and most other terrestrial communications.

OAM modes can play even a more important role in fiber-optic communications, where work on all forms of space-division multiplexing is currently a very hot research topic. Preliminary results on long-range OAM transmission have already been reported. There are many other potential applications of OAM data transmission, including medical imaging and even the detection of landmines.

6. Conclusion

Twisted light has been shown to be the next step in data communication, but tests had shown that standard optical fibers were unable to carry the twisted light beams effectively. But in the present study, the researchers used a new fiber that they had developed previously, which has its own multilayered structure that does not disperse the twisted light. This new optical fiber allowed the twisted light to carry reams of data, but because of its unique design, the fiber itself does not presently have practical use, as most optical fibers used in the world are of standard design.

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