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Twisted light

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Research at the Mathematical Optics Group uses "twisted" light to study new quantum-based information security systems. In order to understand the structure of 'twisted' light, it is useful to start with an ordinary light beam with zero twist, namely a plane wave.

Imagine that one could freeze the plane wave and that one could then visualise the result as a collection of adjacent one-dimensional waves, consisting of troughs and crests. If the crests of all these waves were connected, they would form a surface that looks like an infinite flat plane. In fact, consecutive crests will form consecutive planar surfaces that are parallel to each other and all these surfaces would be perpendicular to the direction in which the light was propagating. These surfaces are known as wavefronts and they are separated from each other by a distance of one wavelength.

Building on this fact that plane waves (ordinary laser light) have flat wavefronts, one would expect the wavefronts for twisted light to be, well, twisted, and this is exactly the case. The wavefronts of twisted light no longer look like those of ordinary light but instead they combine into a corkscrew-shaped wavefronts. Following the same argument as before, if we connect the crests of all the adjacent waves to form the surfaces that define the wavefronts, we find that they have a helical (corkscrew) shape. If we "unfreeze" the beam and watch the movement of the wavefronts, we will see that they rotate around the central beam axis. Near the centre of the beam the wavefronts are twisted to such an extent that they define a singularity, causing the intensity of the light in the centre of the beam to vanish. This dark spot produces the visual distinction between twisted and ordinary light. When ordinary laser light is focussed it appears as a bright point. On the other hand, this is not what happens with twisted light. A focussed twisted light beam produces a ring of light with a dark centre. The size of the dark centre depends on the number of twisted wavefronts present in the light beam.

Another major difference is that the light in a twisted light beam does not propagate directly forward, parallel to the beam axis as in an ordinary light beam, but tends to move sideways in opposite directions on opposite sides of the beam. The net result is that the twisted light beam carries orbital angular momentum (OAM).

Light can be produced with any number of twists. By increasing the number of twists one produces a wave that contains and increasing number of interspersed helical wavefronts. This is dictated by the wave nature of light. The increased number of twists also imply that the sideways movement of the light increases, which in turn produces an increase in OAM. The OAM in a twisted light beam is therefore proportional to the number of twists. If one now considers the quantum nature of light one would discover that each photon in a twisted light beam carries a precise quantum of OAM, which is also proportional to the amount of twist in the light beam. The ability to increase the twist (and thereby the OAM) of a beam of light plays an important role in the applications of twisted light and particularly in secure quantum communication.

Consider a conventional form of communication such as using a flashlight to send a message. In this simple example one would modulate the beam by turning it on and off. This is referred to as binary information transfer, as only two possible choices or states exist. Similarly, Morse messages

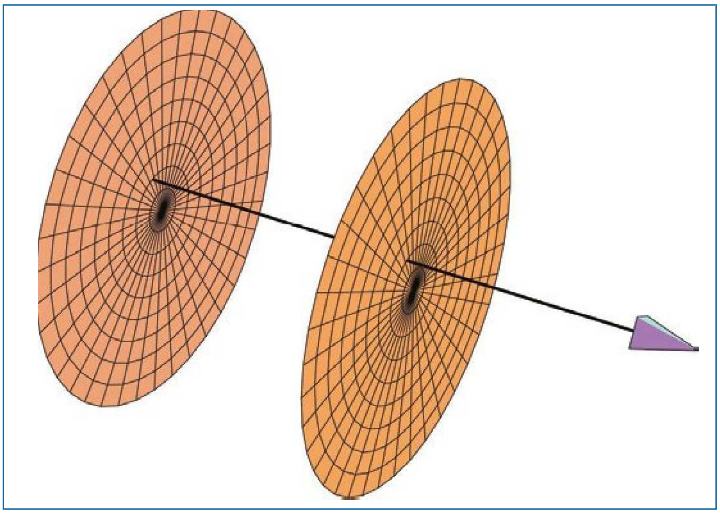

Fig. 1 (a): An illustration of conventional "plane wave", with a surface depicting a flat or plane wavefront. The direction of the energy flow is perpendicular to this flat surface.

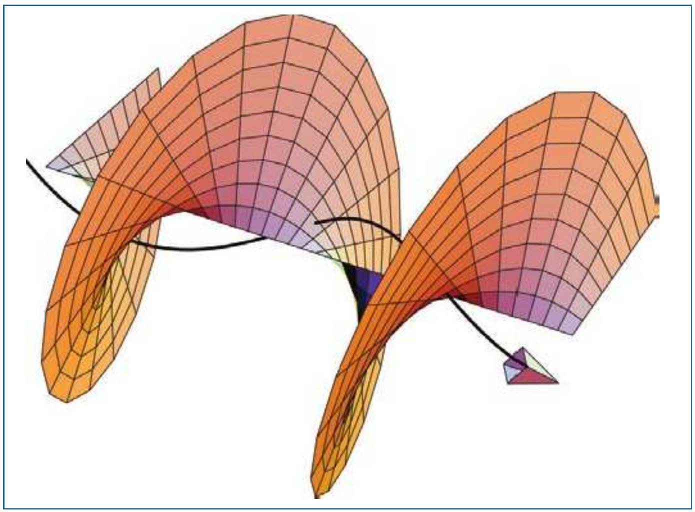

Fig. 1 (b): In twisted light, the wavefront is a helical structure so that the direction of energy flow is a spiral rather than a straight line.

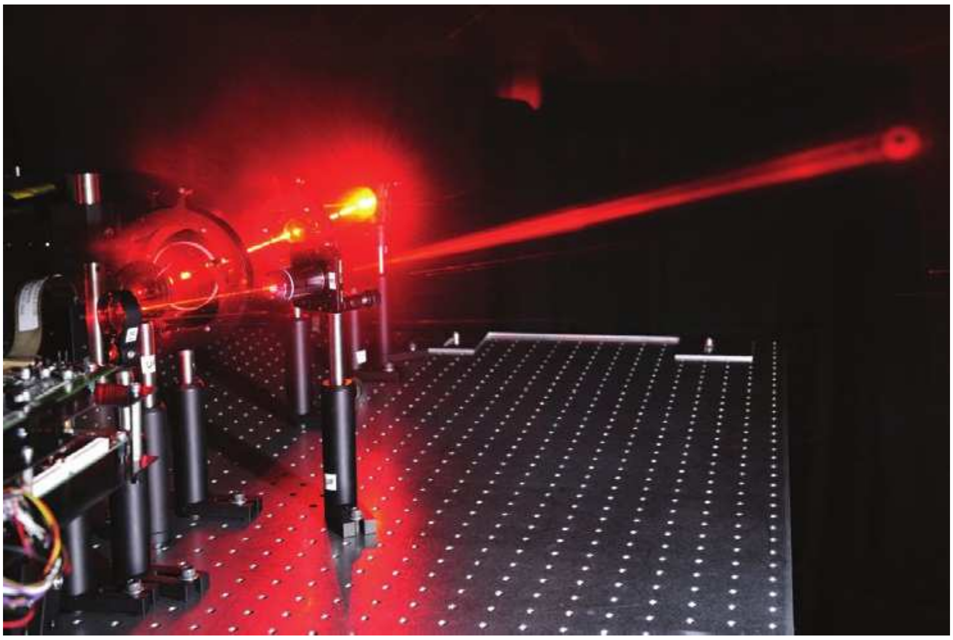

Fig. 2: The generation of twisted light in the laboratory. A red laser is modulated in phase to convert the conventional light into twisted light. Twisted light beams have a dark centre surrounded by a bright ring.

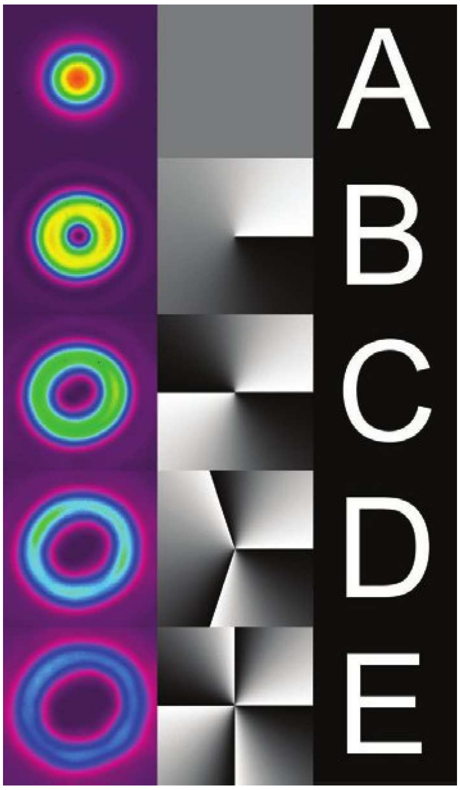

Fig. 3: Examples of the intensity profiles of various orders of twisted light, together with the associated phase: light with no twist (top) to light with four twists (bottom). It is possible in communication systems that the "twists" can be used to encode information, e.g., no twists for the letter A, one twist for the letter B and so on. The phase is shown as a grey scale image with the variation from white to black indicating the number of twists.

can only consist of "dots" and "dashes". In more sophisticated (yet conventional non-quantum) communication schemes (for example, quadrature phase shift key) more levels are used to increase the amount of information per pulse.

Note however, that in all conventional schemes only one specific level can exist in any particular pulse. On the other hand, in quantum communication an object ("pulse") can simultaneously have different states or "levels". One can think of this as different 'realities' that can exist simultaneously. This combination of different realities is called a quantum state. The benefit is that quantum communication allows a certain economy in conveying the information. The objects that carry the information in quantum communication would have the ability to exist in particular quantum states. One would for instance use photons (the quantum particles of light), rather than pulses of light, like those one would produce with a flashlight.

In quantum communications systems the information has, until recently, been encoded in the spin states of photons, which are restricted to only two states (clockwise and anticlockwise), leaving us at the same point as in the flashlight example. The OAM of photons offers an infinite number of possible states, which can be adjusted simply by changing the number of twists in the beam. This opens the way to a "twisted" alphabet: simply set a photon in a single helix (single twist) beam of light to represent the letter "A" a double helix for the letter "B" up until 26 helices for the letter "Z". What is remarkable here, is that because OAM is carried down to the single photon level, one can encode this alphabet at the quantum level.

When two photons are used in the system, it is possible to "entangle" their quantum states in such a way that in each reality there is a fixed relationship between the states of the two photons. Altogether the alternative realities allow all the possible states for each photon, but in every one of the realities the state of one photon dictates the state of the other photon. When a property of one of the photons is measured all but one of the realities would vanish, leaving only one reality, thus fixing the states of both photons. One of the photons would also be destroyed during the measurement.

The property of quantum entanglement allows quantum cryptography to become viable. For two photons that are entangled, only two parties are allowed to take part in the communication process. Any additional eavesdropper would destroy one of the photons and cause all but one of the realities to vanish. This would then be noticed by the legitimate parties and inform them of the existence of the eavesdropper.

In the case of twisted photons, the entanglement is in the OAM states, and offers fundamentally secure communication over an insecure communication channel independent of the adversary's technological advantage. This differs from classical cryptography at the most fundamental level: it is physical laws, rather than computational complexity that provide the security basis of quantum information science. Classical cryptography systems exploit mathematical complexities and computational inefficiencies to distribute encryption keys. The idea is to make it too difficult for your adversary to solve the riddle of what the key is. The security provided by these classical techniques however, are bound by advancements in mathematics and computing power (remember the famous Enigma machine example from World War II). Quantum cryptography using twisted light physically encodes the encryption key within the OAM states of the photons – an application of quantum physics rather than a man-made algorithm. So there is no possibility of cracking this code unless quantum physics as a theory is wrong. If an eavesdropper should try and intercept the message, the quantum states change, modifying the cryptographic key and thereby alerting the legitimate parties involved. Thus quantum systems for secure information are considered to be the technology of the future, and twisted light may just be the enabling technology to make it happen.

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