The twisted future of optical signal modulation

Ransom Stephens - November 20, 2017

By transmitting "twisted light" between buildings separated by a mile in Erlangen, Germany, research engineers and physicists have demonstrated a new optical modulation technique. You're familiar with wavelength division multiplexing (WDM) where different wavelengths (i.e., colors) of light are superposed into a beam with each wavelength carrying a different signal. The new technique could be called OAMDM for "orbital angular momentum division multiplexing." Instead of combining beams of different colors, beams are superposed that are in different states of "orbital angular momentum."

Physics background for "twisted light"
Angular momentum is the rotational version of linear momentum; conservation of angular momentum is the rotational version of Newton's law of conservation of linear momentum. Conservation of angular momentum is the phenomenon that makes it easier to stay balanced on a bicycle when it's moving. You should remember from college chemistry that the periodic table distinguished the elements by their chemical properties and that those properties result from the orbital angular momentum states of the elements' outer electrons. Those states are described by the quantum number \( l \).

The orbital angular momentum of light is also described by the quantum number \( l \), but it's easier to think of it in terms of polarization.

Your sunglasses transmit light with vertical polarization and absorb light with horizontal polarization. We usually think of polarization where the electric field vector of the wave is either horizontal or vertical, so-called planar polarizations. At the photon level, individual photons have circular polarizations: the electric field vector rotates perpendicular to the direction of motion, either clockwise or counter clockwise. These two states of polarization correspond to the two possible states of the photon's spin, +1 or -1 (zero is not allowed because photons are massless; a spin zero photon implies that it must exist in a rest state, but because its going the speed of light in every reference frame photons can never be at rest). Orbital angular momentum in light extends the idea of polarization into beams of light whose Poynting vectors (which describe the direction of energy flow) rotate about the direction of motion.

"Twisted light" is marketing jargon for beams of light in different states of optical orbital angular momentum.

The simple vertical and horizontal polarizations that sunglasses separate result from the superposition of many photons into electromagnetic waves whose net electric fields point in either vertical or horizontal planes. Different optical orbital angular momentum states are composed of
photons superposed in a way that results in discrete values of helicity, but with an important difference. The helicity states are quantized, that is, they only show up in integer steps, and can be formed with just a handful of photons whereas it takes scads and oodles of photons to compose light that is in vertical or horizontal polarization.

**Optical orbital angular momentum modulation**

Use of optical orbital angular momentum modulation at 2.56 Tbits/s using four beams was demonstrated in fibers back in 2012, as reported in Terabit free-space data transmission employing orbital angular momentum multiplexing. It's trickier in free space.

In the new study, "Free-space propagation of high dimensional structured optical fields in an urban environment," two beams of 809 nm wavelength light in different orbital angular momentum states were superposed and transmitted 1.6 km across the Erlangen skyline, above traffic, close to high-rise buildings, and within the noise and atmospheric turbulence of everyday city life, **Figure 1**.

![Figure 1](image)

**Figure 1** The path of twisted light in free space over 1.6 km of the Erlangen skyline (graphic courtesy of the University of Glasgow).

**Figure 2** shows the experimental setup. The source is an 809 nm plane-polarized laser beam focused on a spatial light modulator (SLM). An f-forked hologram displayed on the surface of the SLM "twists" the light into a specific optical orbital angular momentum state.

![Figure 2](image)

**Figure 2** The experimental setup (graphic courtesy of the University of Glasgow).

Where a photograph records the intensity of light, a hologram records the diffraction pattern of light; that is, a photo records power, a hologram records phase. The f-forked histogram fixes the phase relationships of the light in a way that puts them in specific states of orbital angular momentum.

The two lenses, L1 and L2 form a telescope that magnifies the beam to a 40 mm diameter. The beam propagates over Erlangen to the receiver, which collects and focuses the light onto a beam splitter. One of the resulting beams is focused on camera C1 and the other is passed through an orbital
angular momentum mode sorter, MS, and the second camera, C2, measures its OAM content.

So what’s the big deal? You modulate red light and shine it from one building to the other. Nothing to it, right? The difficulty is in whether or not the integrity of the angular momentum states of the beam can survive atmospheric turbulence. You see, back in the 19th century, the great British physicist, Lord Rayleigh taught us that the sky is blue because light is scattered by air molecules. Anyway, it turns out that quantum states like orbital angular momentum are notoriously difficult to maintain outside the calm of a laboratory. As pressure fluctuations in the air scatter the light, the orbital angular momentum state of the beam is likely to change and ruin the signal’s integrity.

In this experiment, the signals were successfully demodulated, though the different orbital angular momentum states suffered different losses. Figure 3 shows four cases. Each beam consists of a combination of two orbital angular momentum states, $+l$ and $-l$ where $l$ ranges from 1 to 4; the power loss ranges from 5.6 dB for $l = \pm 1$, 10.3 dB down to 37.7 dB for $l = \pm 4$. 

A \hspace{1cm} \ell = 1

B \hspace{1cm} \ell = 2

C \hspace{1cm} \ell = 3

D \hspace{1cm} \ell = 4

E \hspace{1cm} \text{Power loss} \approx 5.64 \text{ dB}

F \hspace{1cm} \text{Power loss} \approx 10.29 \text{ dB}

G \hspace{1cm} \text{Power loss} \approx 22.32 \text{ dB}

H \hspace{1cm} \text{Power loss} \approx 37.7 \text{ dB}
This experiment serves as proof of principle that optical orbital angular momentum states can be used to multiplex signals into a single beam that can propagate across long distances, a whole new approach to wireless point-to-point data transmission.

Because the scheme is built on orbital angular momentum quantum states, it also demonstrates the phenomenon of entanglement (I’ll write about entanglement soon, in the meantime, read Chapter 1 of Volume 3 of the *Feynman Lectures on Physics*, it’s probably the greatest single chapter in the annals of physics), which means that applications of *quantum cryptography* are likely to follow.

—Ransom Stephens is a technologist, science writer, novelist, and Raiders fan, even when his team loses 33-8.

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