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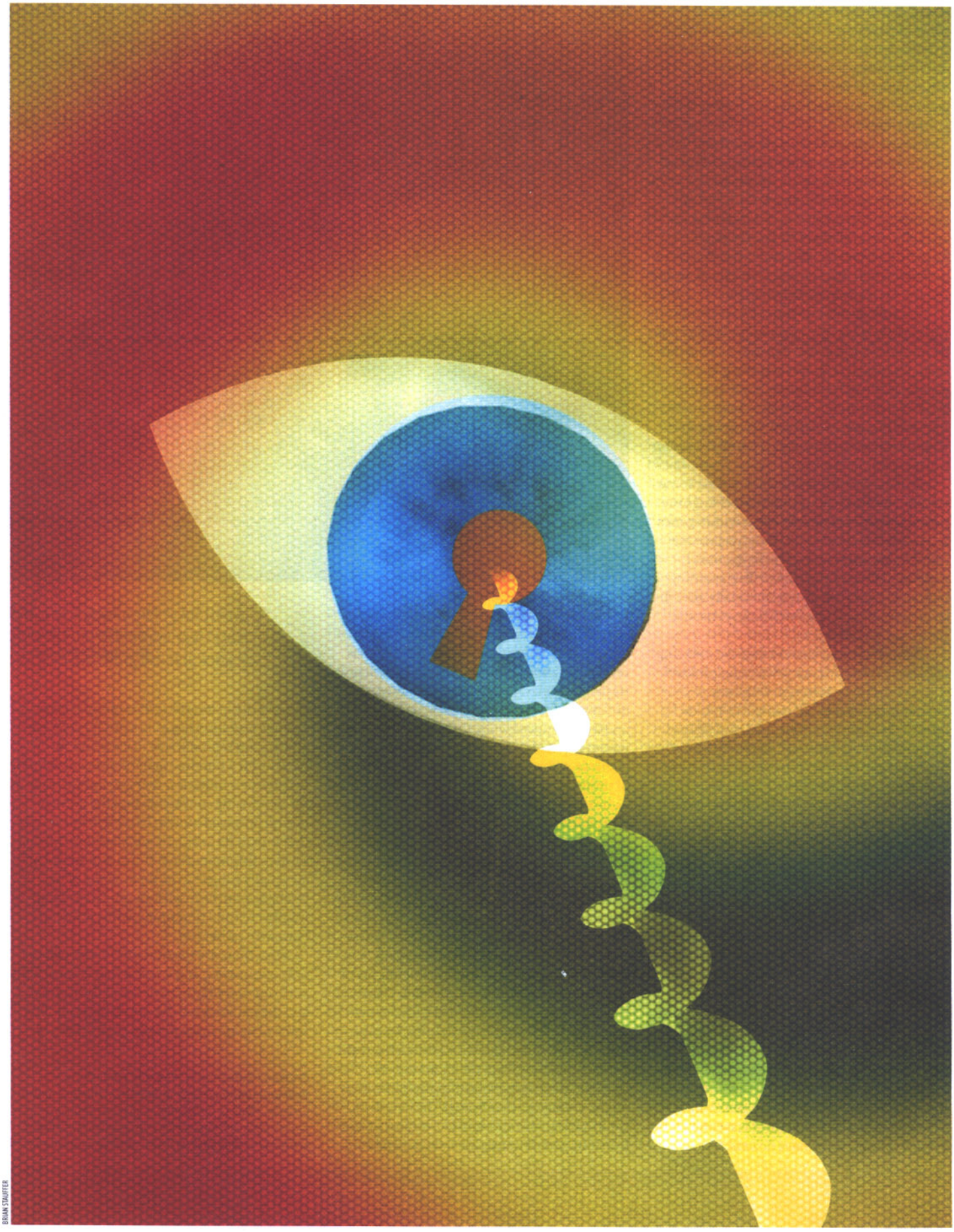


BRIAN STAUFFER

A novel trick with light has got physicists in a spin. Pitch your photon like a corkscrewing curveball and you can push bandwidth through the roof, flummox eavesdroppers and perhaps even talk to aliens. **Stephen Battersby** investigates

Twisting the light away

IT DOESN'T look like much, just a plain box about half a metre long. Nonetheless, this is the prototype of something with seemingly magical properties. Fire a beam of its laser light at the dust sitting on your tabletop and the dust motes will begin to dance around in circles.

Fair enough, that's not quite a killer application. But before Miles Padgett and his team at the University of Glasgow in the UK built this device, they weren't exactly sure what it would be used for – their plan was to invite industrialists to see it in action, and wait for the reaction and some suggestions. Without a working model, though, no one would take them seriously. "If you say to people, there's a device we haven't built yet, based on untried technology, using physics you've never heard of, but I assure you it's going to work...well, it's much better to demonstrate it to them."

So they built it and demonstrated it, and now the applications have become clear – and sought after. This box is the prototype for what could prove a revolutionary, high-security communications technology. Revolutionary to us, that is. Alien civilisations may be using it already.

Padgett's box creates something most physicists have never even heard of, something never seen in nature. It is called twisted light.

The energy of ordinary light travels in the same direction as the wave: if you could freeze an ordinary beam of laser light, you would see a neat series of waves, crest following trough following crest. Each wave crest would look a bit like a pancake face on to the direction of travel, with the pancakes slicing the beam up into sections one wavelength long.

But in a beam of twisted light the energy of each wave travels in a corkscrew path, spiralling around the beam's central axis. The crests also look completely different to those of ordinary light: they are transformed so that they merge into a corkscrew (see Graphic, page 38). If you could stand on a wave crest and walk around the beam, after one complete circuit you would find yourself standing one wavelength away from where you started.

Though twisted light might sound exotic, making it is surprisingly easy. All you need is a diffraction grating – nothing more than a set of narrow lines drawn on a transparent film. The light waves bend, or diffract, as they pass through the grating, and then interfere with each other as they emerge. For light of a particular wavelength, diffraction occurs in a way that can be easily calculated, and physicists can work out what pattern of lines they need on the grating to create a twisted beam. You can produce a single helix, a double helix like DNA, a triple one like fusilli pasta, a quadruple one, or even more. You can even alter the grating pattern to make a terrifically screwy beam with a twist of 250 or more.

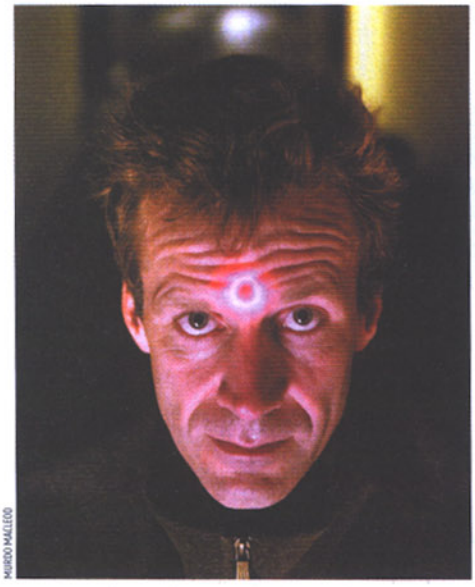
Sending laser light through such a grating actually imparts twist to the individual photons – the energy-carrying particles of light – in the beam. In quantum physics terms, the photons in the beam gain orbital angular momentum (see "The quantum angle", page 40). Unlike polarisation, which is restricted to just two states (clockwise and anticlockwise), orbital angular momentum can take on an unlimited number of possible states. And that's one reason why twisty light could prove so useful. The endless number of twist states means there is no theoretical limit to the amount of information you can send with a beam of twisted light.

Many forms of communication use binary codes – if you have a flashlight, and you need to send a message to your friend, you only have the choice between flashlight on and flashlight off. There's just one bit of information per flash. Standard optical telecoms work in a similar way, but use light pulses of several frequencies at once to speed up the process. Even highly sophisticated quantum communication systems only encode information in one of the two polarisation states of a photon.

But a pulse of twisted light, even a single twisted photon, can hold a lot more information than that, because there are a lot more states to choose from. "With a twist of up to 26 you could choose to encode the alphabet," says Padgett. You could simply decide that a flash of single helix light means the letter A, a flash of double helix is B, and so on.

The idea of using twisted light to communicate was first raised in 2002 by ▶

Miles Padgett's corkscrew laser beam creates a ring of light with a dark centre



MURDO MACLEOD

MURDO MACLEOD

Gabriel Molina-Terriza, then at the Technical University of Catalonia in Barcelona (*Physical Review Letters*, vol 88, p 13601). However, Molina-Terriza's team faced a practical snag: they didn't have a good way to receive a twisted light signal – to tell what twist it has. Without that, communication would be impossible.

But the solution wasn't far off. Padgett and his Glasgow group had already been using twisted light to create an "optical spanner", which is able to spin tiny components (and dust motes), and one day might be used to build microscopic machines (*New Scientist*, 14 February 1998, p 34). When they heard Molina-Terriza's suggestion, the team realised they could turn their twisted expertise to communication.

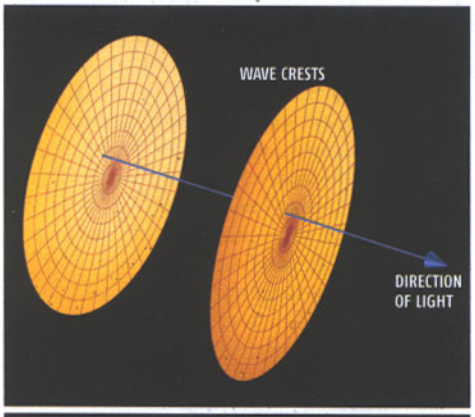
The heart of their prototype is a spatial light modulator (See Graphic, page 39). This is a high-resolution liquid-crystal display which can be used as a kind of controllable diffraction grating. A laser beam is blocked by the opaque pixels, and passes through the transparent pixels. Where the light passes through it is diffracted, bending the shape of the wave.

Together with Steve Barnett and his theory group at the University of Strathclyde in Glasgow, Johannes Courtial of Padgett's team worked out what patterns were needed to give a plain laser beam any one of eight different

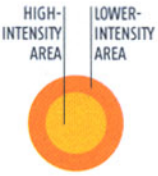
Giving laser beams a twist could provide a new way to create secure communications

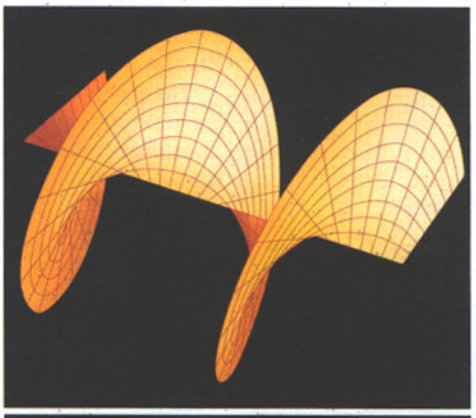
CORKSCREW LIGHT

By giving laser photons orbital angular momentum, the wavefronts of light become twisted. To see the twist, researchers interfere the twisted light with normal laser light

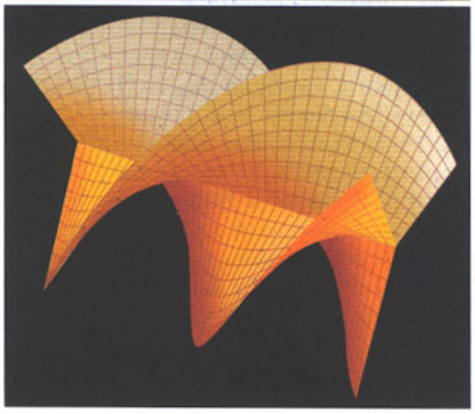


Twist = 0 (normal light)
A normal laser light spot viewed in cross section

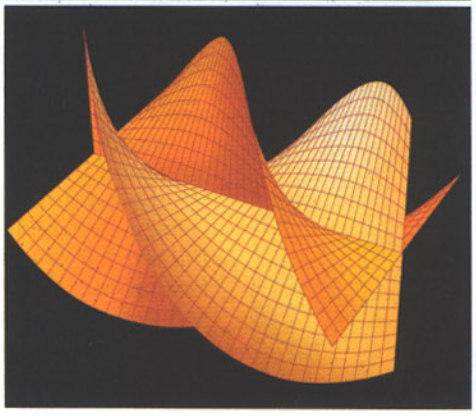




Twist = 1
A single corkscrew beam has a spiral-shaped cross section



Twist = 3
The number of bright patches reveals the twist number

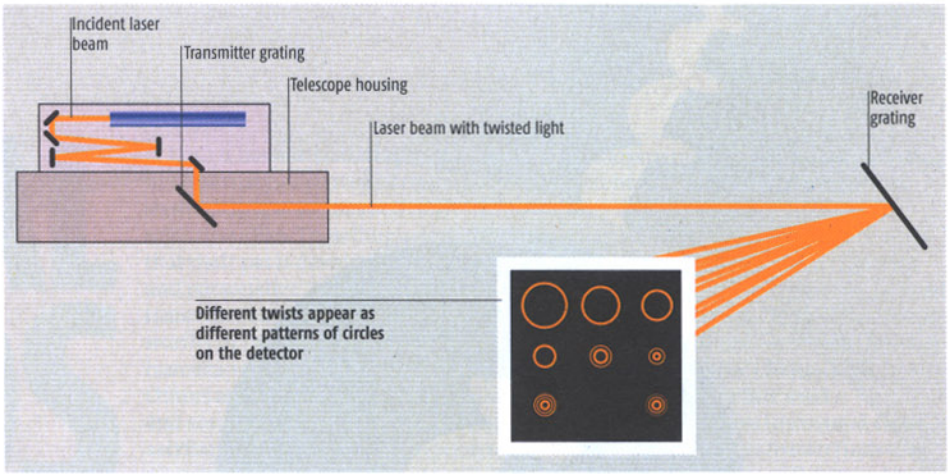


Twist = -4
Light can be given a left or right-hand twist. Here it is right-handed

"Unless you are right at the centre of the twisted beam, where you can see the whole spiral, you can't get all the information it carries"

PROTOTYPE FOR TWISTED-LIGHT COMMUNICATION

The transmitter grating diffracts laser light giving it a twist. The twisted light is spread by the receiver grating in directions that depend on the twist



twists. They just switched the pattern on their spatial light modulator to send a pulse of a given twist.

The receiver is slightly different. It focuses the incoming beam onto another spatial light modulator, but this one is programmed with a fixed pattern that sends each of those eight different twists out in a different direction, travelling to one of eight detectors.

Last April, Graham Gibson of the University of Glasgow began to put a prototype together, cannibalising an old air-pollution monitoring system the group had built years before. Everything went smoothly, and early this year they got it working. "We've taken it outside and used it over 30 metres or so," says Padgett.

Twisted talk

The Glasgow team are the first to harness the power of twisted light for communications. Their prototype can send light pulses with eight different twists, so a pulse carries the equivalent of three bits of information. It should easily be possible to increase that to 64 twist states, carrying six times the data of an ordinary binary channel.

So, how far could it go? "In theory, you could encode all 60,000 Chinese characters," says Padgett, "but by that point it becomes unpractical." That's because the twistier the light, the more the beam loses focus and spreads as it travels. Padgett reckons the practical limit may be somewhere in the hundreds of twist states.

That still makes it an enticing prospect for carrying data at unprecedented rates. At the moment, there's not much call for beaming optical messages through free space. Fibres are another matter. If you could send twisted light down the existing optical-fibre network, its greater bandwidth could carry extra movie channels, or even allow more futuristic, data-hungry applications such as online 3D virtual reality. There's just one small problem: twisted light is not compatible with today's optical fibres. "If it were, I'd have retired to the south of France on a yacht by now," says Padgett. The problem is that if you stress the fibre at all, even by bending it round a corner, it changes the twist.

However, it should eventually be possible to design fibres that can safely carry twisted light. Padgett thinks that multi-cored fibres might be an answer – a fibre with 16 separate cores might be able to carry twists of up to 16 without scrambling them. But for now that's just a guess: he doesn't know exactly how you would need to arrange the cores, or whether it would work. Meanwhile, a team led by Alexander Volyar at Tavrichesky National University in Ukraine is working on physically twisting fibres to accommodate twisted light.

Another magical property of twisted light may prove valuable before that. It offers a whole new approach to secure communications – an approach that is already provoking interest. In February, a commercial organisation approached Padgett's group with a specific application in mind. Unfortunately Padgett can't say what that is, or even name the interested party. "We have a non-disclosure agreement – including company names," he says.

Padgett will say, however, that his group has begun work on a microwave version of the device. There may be little call for free-space communication at visible wavelengths, but point-to-point microwave systems are ubiquitous, for example, carrying cellphone traffic between base stations. Because microwave beams spread out much more than optical beams, it is much easier to eavesdrop on microwave communication. You can be hundreds of metres away from the intended receiver and still pick up enough of a signal to listen in. And that's where twisted microwaves could help.

Unless you are right at the centre of the ▶

SPIRALLING SECURITY

If Alice sends Bob a twisted light beam, and Eve wants to listen in, she's going to have a hard time of it. If she's in the neighbouring office block, say, she can only pick up one fringe of the beam. She can't see the whole pattern of wavefronts, so she won't be able to tell how twisted it is. She will get just a fraction of the information, which would be useless.

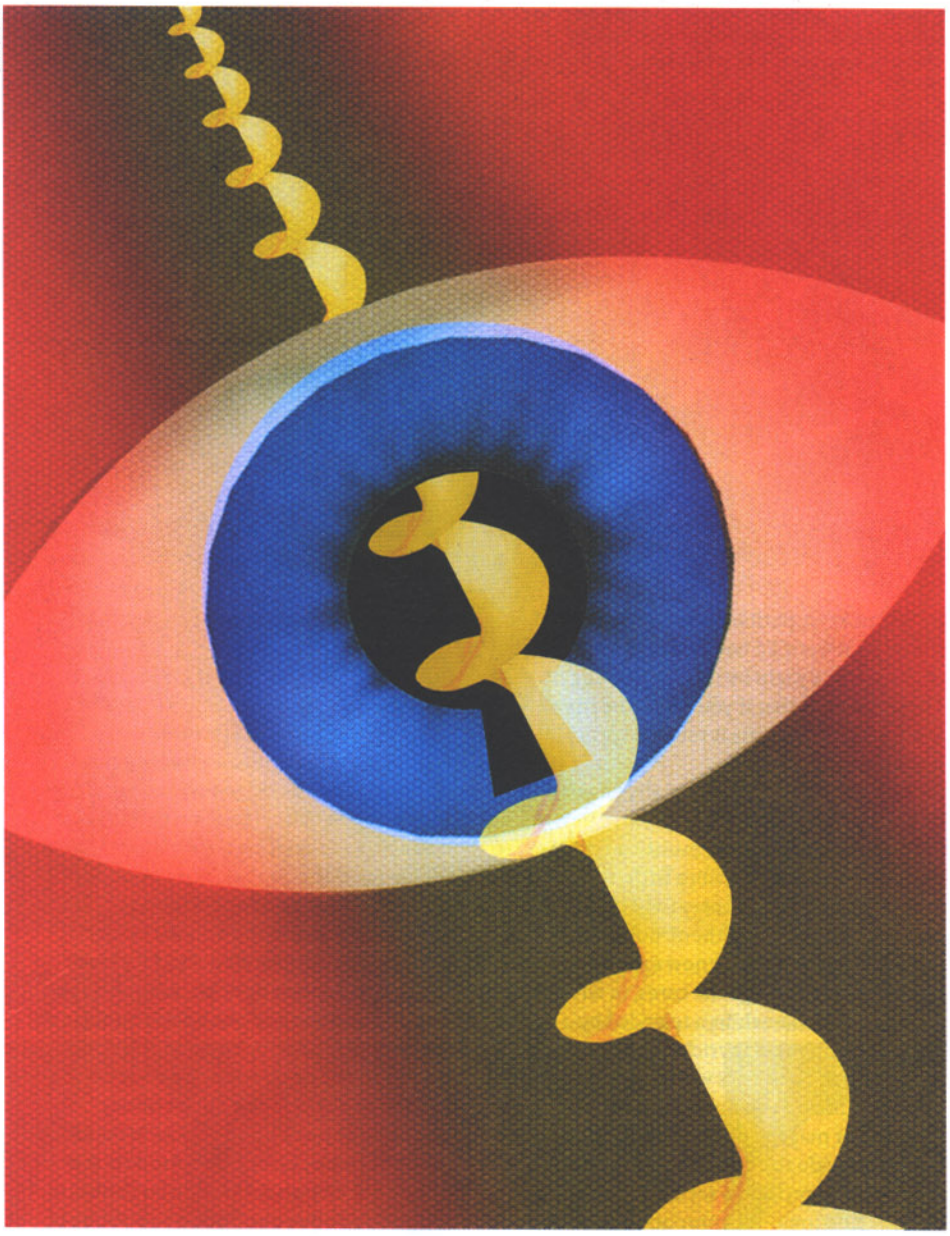
Maybe Eve could recruit some evil henchmen, and have them intercept other bits of the beam? "If they have someone right, left, below and above, they can do a better job," says Miles Padgett. But still not good enough. Eve would probably need eight listeners, dotted evenly around the edges of the beam, to be able to discern its twist reliably.

And to compare the relative phase of the different parts of the beam, which you need to do to determine its twist, the listeners have to combine the light they gather – maybe they could bounce it off mirrors to some main collecting station where it could all be recombined. They would also have to use their own laser reference beams to correct for any wobbles.

Even if this mad scheme worked, it would be easy enough for Alice to increase the range of twist states from eight to 64, say. Eve would then need to recruit several dozen spies.

Eve can't dangle a detector in the middle of the beam because Bob will notice that he's not seeing the whole beam. She could make a lightly silvered mirror, and bounce a little of the light away to the side, but it would be tricky. She would need to know just where the middle of the beam is, and somehow suspend her mirror there. And taking so little light would make it difficult to extract the twist information. Alice can make the beam quite weak, so Bob has just enough light to detect its twist. If Eve sees only a small fraction of that, analysing it could be all but impossible. "In theory it's possible to do this so delicately that the receiver doesn't know there is eavesdropping. But it would be exceptionally awkward," says Padgett.

BRIAN STAUFFER



twisted beam, where you can see the whole spiral, you can't get all the information it carries. Off centre, where you only see a section of the spiral, you simply can't tell what its twist is – so you can't read the message (see "Spiralling security", page 39).

For those with enough cash and the paranoia, the security of twisted light could also be combined with the impenetrability of quantum cryptography. Quantum-cryptographic systems, which are already commercially available, establish a key via single photons fired along a fibre-optic cable. The receiver can check them for the quantum disturbances that any eavesdropper would introduce, thus guaranteeing that the key has not been intercepted.

Messages in space

Although quantum cryptography is totally secure in theory, building the actual physical set-up can introduce weaknesses that an ingenious eavesdropper could exploit (*New Scientist*, 29 November 2003, p 24). And data rates are very slow: commercial systems generate keys at a few hundred bits per second – not even enough to encrypt a telephone conversation. But combine quantum cryptography with the extra bandwidth of twisted light and you might boost the capacity tenfold or more, enough to make truly secure communication practical. Twisted light could well end up as a common cryptographic tool for financial institutions – perhaps for beaming sensitive information between skyscrapers – or on the battlefield.

It could also end up in space. Most satellites communicate via microwave beams, which spread widely by the time they hit the ground, making it simple to eavesdrop on an ordinary beam. Again, twisted microwaves could make the message accessible only to the intended receiver at the beam's core. Although the team haven't tested their rig over such long ranges, they say there is no reason why it shouldn't work in principle.

If we do point twisted-light detectors up to space, it's just possible that we might see more than we bargained for. Martin Harwit, emeritus professor in astronomy at Cornell University in New York, has suggested we start looking for twisted light from space as part of the search for extraterrestrial intelligence. Since no known natural phenomenon can create a coherent beam of electromagnetic radiation with, say, a sixfold helix, it would stand out from the background noise of the universe as a deliberate call sign.

It certainly makes looking for ordinary radio signals seem a little backward. So, until we have mastered its use here on Earth, maybe we should pursue twisted light as a matter of pride. Perhaps talking with twists will come to be known as the mark of a truly advanced civilisation. ●

THE QUANTUM ANGLE

Can even a single photon be twisted? If you think about light as a classical wave, then twisted light is like a corkscrew, with the wave fronts bent into a single or multiple helix. But it's hard to see how that makes sense for a single quantum of light, a photon. So until a few years ago, physicists thought that twist might only be a property of big beams of light.

In 1992 Les Allen of the University of St Andrews in the UK showed that twisted light carries angular momentum, like a flywheel. For singly twisted light, it works out at one quantum unit of angular momentum per photon, so Allen suggested that this "orbital angular momentum" is a property of the individual photons.

In 2001 Alois Mair, now at Harvard University, worked with Anton Zeilinger's group at the University of Vienna, Austria, to prove it. They created entangled pairs of twisted photons, and showed that the twist resides in each photon (*Nature*, vol 412, p 313).

A twisted photon is a curious thing. It appears to travel along a helical path, as if it is tied to some imaginary beam axis with string. If you detect it anywhere along the beam, it will seem to be coming at you from an angle – its momentum is not directed straight along the beam, but partly around the beam's axis. Of course, being a quantum object means it doesn't really move along a well-defined path at all. All you can say is how likely you are to detect it in a given spot, which gives you a spread-out quantum wave function.

And what does the wave function of a twisted photon look like? Exactly like the corkscrew of classical twisted light.