LEADING LIGHTS

Shape it, squeeze it, energize it or tie it into knots. Scientists are taking light to new extremes.

| BY ELIZABETH GIBNEY |

THE PHOTOGRAPHIC UNIT/UNIV. GLASGOW

| SHAPING LIGHT |

Miles Padgett

Physicist Miles Padgett starts to describe the concept of twisted light by taking down a rainbow-coloured spiral that hangs from the ceiling of his office at the University of Glasgow, UK. Then he stops and scours the room for more props: dinner plates, paper, pencils and even leftover Christmas chocolates.

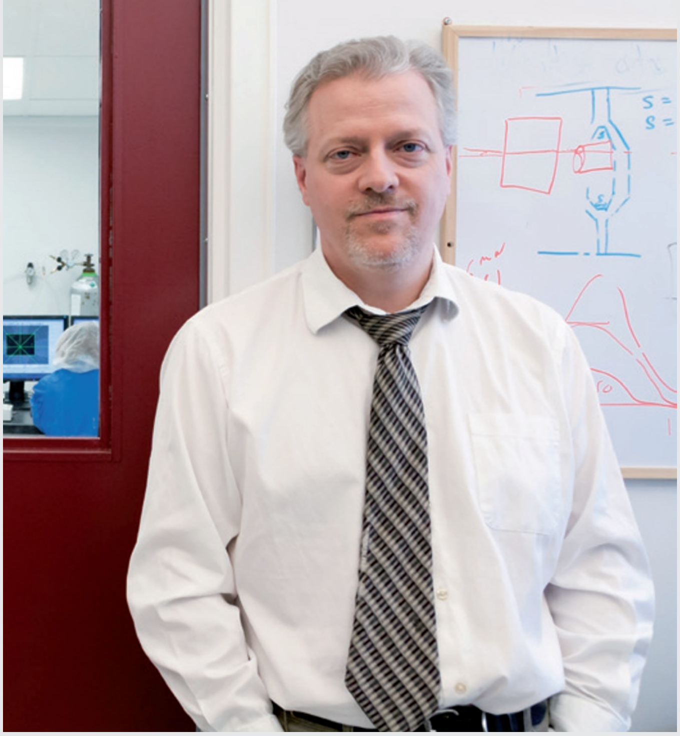
Light is made of oscillating electric and magnetic fields, he explains. In a conventional laser beam, the oscillations are always in step, with the peaks and troughs lined up from one side of the beam to the other. (Padgett illustrates the flat, planar waves with a stack of dinner plates that he moves face-forward.)

But things get more interesting when parts of the beam fall out of step. This is where Padgett points to the spiral: the peaks of the wavefront can be manipulated to the point at which they curl around the beam's direction of motion in a corkscrew. This is twisted light, says Padgett, who has spent two decades learning to exploit its unique properties.

He has pioneered applications that range from moving cells without physically touching them to packing lots of information into an optical signal — and even tying light in knots. In the process, he has developed a rare instinct for the subject, say collaborators and colleagues. "Many other scientists might need to do a calculation, run a model or do an experiment before they can get an idea about how light should behave," says Mark Dennis, a theoretical physicist at the University of Bristol, UK. "One of Miles's great talents is having this knack at being able to anticipate what the results should be."

Props are not the only thing in Padgett's office. It houses the lab's coffee machine, and doubles as its kitchen and common room — complete with sink. Padgett is a fan of productive chance encounters, and likes to keep the place buzzing with people picking each other's brains.

It was a chance encounter that led him to twisted light in the first place. In 1994, as a research fellow at the University of St Andrews, UK, he had dinner with physicist Les Allen intending to discuss laser technology. But the conversation turned to Allen's experiments with twisted light[1]. Allen, then at the University of Essex in Colchester, UK, baited Padgett by saying that he knew how to give the light its twist using the stem of his wine glass as a lens. This strange idea had Padgett hooked. By 1997,



PETER THORNTON/UNIV. OTTAWA

| SQUEEZING LIGHT |

Pierre Berini

Pierre Berini knows a bargain when he sees one; the evidence is in his lab, which is cluttered with lasers, oscillators and other components that he bought at auctions after local companies folded. The University of Ottawa physicist often buys in batches, after spotting essential items in a job lot that otherwise looks like junk. "There are lots of surprises," he says.

Berini has a certain sympathy for the failed companies. He is a leader in plasmonics, a way of manipulating electrons with light that could be used to transmit information in super-fast computers. Months after launching a venture-backed firm, Spectalis, to market plasmonics circuitry to the communications industry in the early 2000s, he began to feel the effects of the dot-com bubble bursting. He ended up hosting an auction of his own and closing shop. Unperturbed, he plans to try again this year, launching a company to apply his technology to tiny sensors in handheld devices that detect diseases rapidly and with extreme sensitivity.

The devices use a peculiar kind of light that emerges from waves ▶

he and his colleagues had not only learned how to make twisted light for themselves, but had also devised a way for it to function as an 'optical spanner' to trap cells and other microscopic particles, then rotate them into any position[2].

Turning light into a spanner is really about shaping it, Padgett says. A very simple example of shaping is a digital projector, which creates a changing image by altering a beam's intensity pixel by pixel. A more sophisticated example is a liquid-crystal device that does nothing to the intensity of the light passing through each pixel, but instead shifts its 'phase' — the relative position of the wave's peaks and troughs. In the stacked-dinner-plate analogy, the plates collectively warp and bend.

Getting to twisted light is a matter of taking that warping to extremes — so that the wavefronts form a spiral. That twist means that the beam not only exerts radiation pressure on the objects it encounters, nudging them forward, but also tries to rotate them. "It's just like turning and pushing a door knob to open a door," says Padgett. The optical spanner passes this momentum to microscopic objects to trap, rotate and move them. Using such devices, biologists can bump beads into cells to measure the cells' stiffness, and engineers can create unique nanoscale materials.

Twisted light also provides a new way to encode information. The conventional approach to doing this with light is to encode each bit as a single photon spinning either clockwise or anticlockwise around its direction of motion. Quantum mechanics allows only those two possibilities, so this gives a natural way to represent the 1s and 0s of binary code.

But twisted light has an extra rotational quantity known as orbital angular momentum. This differs from intrinsic spin in the same way as Earth's yearly motion around the Sun differs from its daily rotation on its axis. And it is much less constrained by quantum mechanics. In theory, says Padgett, twisted light can have an infinite number of orbital angular momentum patterns, or modes, each twisted tighter than the last. "This is like having a whole alphabet with which to communicate," he says.

A decade ago, Padgett was among the first to show that each mode can be used to encode different information[3] — such as shades of grey or numbers — which allows much more data to be carried by the same optical signal than is possible with just spin encoding. Last year, a team at the University of Vienna encoded grey-scale images of Wolfgang Amadeus Mozart and other famous Austrians using 16 twisted modes, and successfully sent the images through 3 kilometres of air[4] (see *Nature* http://doi.org/ztt; 2014). By using extra channels of information, such techniques could increase the data-carrying capacity of fibre-optic cables and radio waves.

> *"This is like having a whole alphabet with which to communicate."*

Padgett has found even more imaginative ways to play with twisted light. When a beam of it illuminates a wall, for example, the spot will have a dark centre. That is because a spinning beam of light has a vortex in the middle where intensity is zero. Look closely at a spot of laser light, says Padgett, and it seems to be riddled with such dark spots, known as speckles. If you could trace these spots back through the laser beam, they would form continuous lines of zero intensity twining in three dimensions[5]. "These can be like cooked spaghetti, or you can form them into spaghetti hoops or even chain mail," says Padgett. (He points to a poster on his wall showing what that looks like: its title is 'Speckle-ghetti'.) In 2010, he and his collaborators showed how to form the lines into knots[6]. It took theorist Mark Dennis at the University of Bristol, UK, a decade to create the complex mathematical recipe of overlapping beams needed to make an isolated, pretzel-like knot. Only with the recipe in hand could Padgett's team use its light-shaping skills to make the abstract mathematics a physical reality.

Padgett believes that the best way for a person to succeed is for them to find something they are good at, and then to apply it everywhere. "Our team can shape light beams," he says. "So we use shaped light in communications, microscopy, in imaging, in sensors. We always ask, how can we apply what we know to areas that others are interested in?" He is using that philosophy in his latest project: leading the Quantum Imaging Hub, a collaboration between 6 universities and 30 companies, which is one of the 4 Quantum Technology Hubs launched last November by the UK government. His group is creating infrared cameras that use a single-pixel detector rather than the millions of expensive pixels in a conventional camera. By projecting masks of black and white squares onto an object, flickering 20,000 times a second, the team can measure how incoming intensity varies, and reconstruct a picture[7]. "It's a convoluted, but much cheaper, way of doing the job," says Matthew Edgar, a physicist in Padgett's lab. With image-compression techniques and boosted computer power, the team hopes to extend the technique to video, allowing infrared cameras to spot gas leaks or see through smoke.

Back in his office and packing up to head into the Glasgow rain, Padgett reflects on what he loves about light. It is not its endless uses. Instead, he says, the beauty of light is that the more deeply you understand it, the more straightforward it gets. "If light ever surprises me, it's not in its complexity, but that it is so simple," he says. ■

of electrons propagating across a metal surface in contact with an insulator, such as air or glass. When excited with a laser, these charges, or plasmons, generate fluctuating electric and magnetic fields that flow just above the metal surface. Trapped at the interface, the waves can be funnelled into structures that confine their wavelengths to a few tens of nanometres — as little as one-tenth of the laser's wavelength. The squeezed waves travel more slowly than laser light, so can retain the same frequency.

Berini backed into studying plasmonics while looking for ways to improve normal electrical components and photo detectors in the late 1990s. Light travels much faster than electrical signals, so using it to connect silicon chips would massively speed up calculations. But light is limited by its wavelength: although electronic devices can be shrunk to a few tens of nanometres, the infrared light used in telecommunications cannot focus to spots much smaller than a micrometre. "It's a fundamental incompatibility," says Berini. The smaller wavelengths available with plasmons looked promising, but plasmonic light does not always behave. The waves, created by the movement of electrons, decay quickly as a result of resistance in the metal, and they travel only micrometres.

Berini used tools that can craft nanoscale structures, which were becoming cheaper and more readily available, to create the first plasmonic waves that could travel for centimetres (ref. 8). His lab made whole circuits, guiding plasmons down metal strips less than 30 nanometres thick.

But allowing the waves to travel farther increases the light's wavelength. Although plasmonic waves are still smaller than conventional light waves, the compromise lessened their advantage and Berini found it tough to crack the telecommunications industry, where each component in use

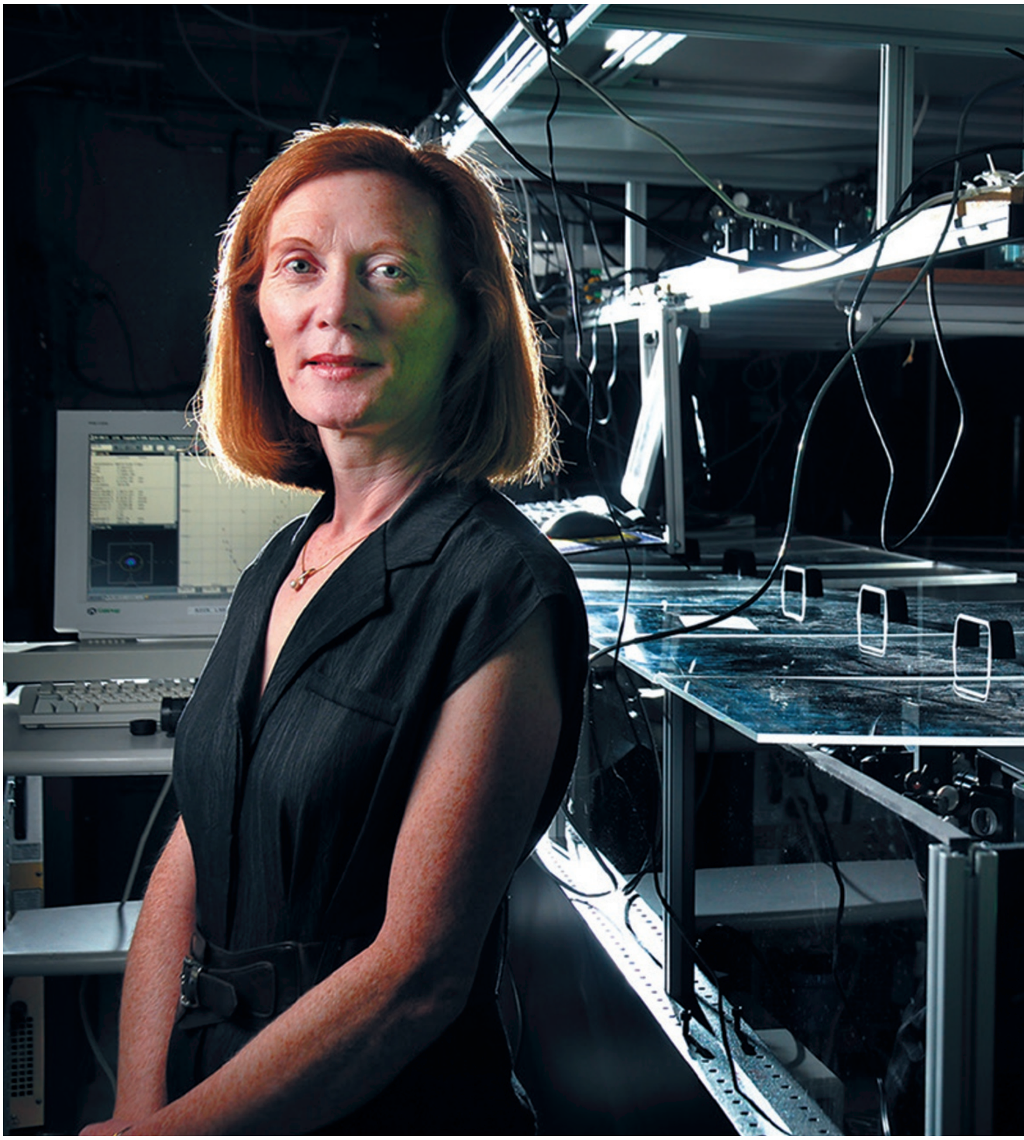
| FAST LIGHT |

Margaret Murnane

When Margaret Murnane was growing up in rural County Limerick, Ireland, in the 1960s, she had no talent for activities considered suitable for girls, such as sewing or art, and never thought of herself as being good with her hands. What she did enjoy was going on long walks with her father, and gazing at rain-drenched Ireland's multitude of rainbows — an activity that led to a lifelong fascination with light. In following that passion, she says, "it turned out I have a talent I never knew for aligning lasers. But in normal life, how would you ever know?"

Murnane's life is now that of a physicist at JILA in Boulder, Colorado, a joint institute between the University of Colorado and the US National Institute of Standards and Technology. There, with husband Henry Kapteyn, she runs a lab that is leading development of an X-ray laser that strobes in attosecond pulses, each blast lasting just one-billionth of one-billionth of a second — almost the same proportion of a second as that second is of the entire age of the Universe. Such ultrafast X-rays, which have tiny wavelengths and high energies, are often used to penetrate deep into atoms and image them at the nanometre scale. Usually, this happens at billion-dollar facilities that generate X-rays by accelerating electrons to near light speeds, such as the SLAC Linac Coherent Light Source in Menlo Park, California. By contrast, Murnane's set-up fits on a dining-room table. It allows scientists to watch the movement of electrons around atoms, probing chemical bonds or studying spins in a magnetic hard drive.

Murnane's background — a childhood spent without central heating or indoor plumbing, but with a love of knowledge and learning — lies behind much of her drive, says Kapteyn. "She worked her way up," he says. Murnane met Kapteyn as a graduate student at the University of California, Berkeley, and the two



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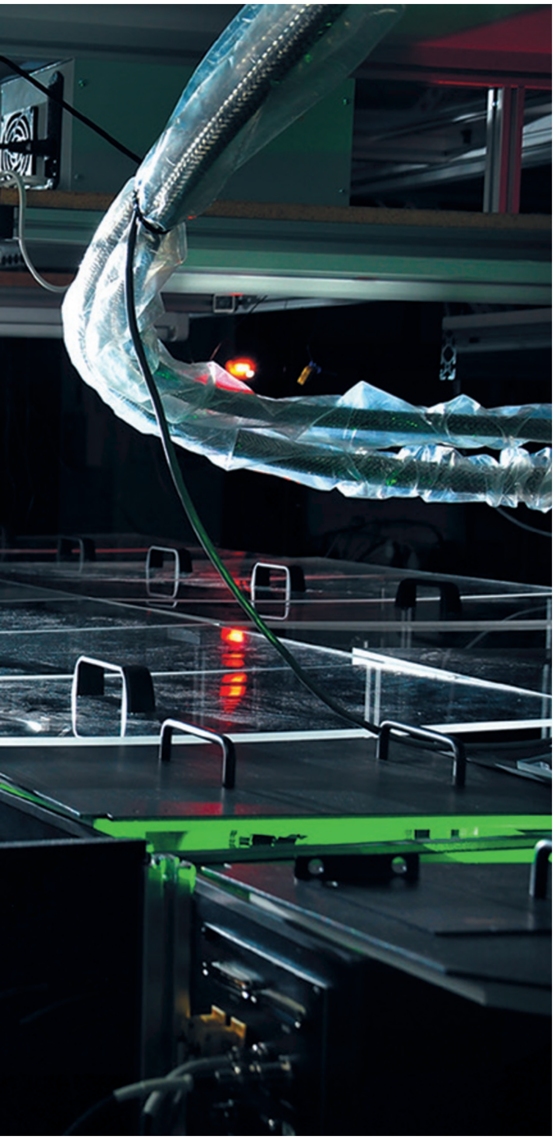
have worked together ever since — forming a stable partnership that Murnane believes underlies their scientific success. "It helps to have someone who will challenge you hard. Those relationships are good for science, but difficult for individuals to learn," she says.

Together they tackled a problem that they first attempted in graduate school — how to generate laser-like light beams at high energies. Rather than accelerating electrons, as huge facilities do, their strategy was to combine many visible-light photons into a handful of higher-energy X-ray photons. The process has an analogy with sound. In stringed instruments, plucking a string gently generates a single tone. "If you pluck it harder and harder, had been honed over decades. So he and others have been busy developing other techniques to deal with the short range of plasmonic light, either branching out into applications that turn the loss into an advantage, such as photodetectors, or by using nanostructures to amplify the waves. Physicists are now developing an assortment of nanoshapes — stars, rods and crescents — in a range of materials that could harness these waves for applications such as capturing solar energy, killing cancer cells and creating chip-integrated lasers, known as spasers.

Henry Schriemer, a physicist at the University of Ottawa, calls Berini a "quintessential experimentalist with a deep appreciation for the theory". But Berini says that it is applications that turn his lab on; he attributes this entrepreneurial bent to his parents, who ran their own businesses in Timmins, the Ontario mining and logging community where he grew up.

Today, Berini is recycling the efforts made in long-range circuits to make a detector for dengue fever. The device, a handheld biosensor developed last year with researchers at the University of Malaya in Kuala Lumpur, sends plasmon waves down a chip scattered with dengue virus particles. A blood sample is placed on the chip; if the donor has the infection, the sample will contain antibodies that bind to the virus, disrupting the wave and producing a signal[9]. Berini says that the sensors could speed up diagnosis, which normally involves sending samples away to a lab.

A new company is now in the works to commercialize a range of similar biosensors. But Berini believes that the application is just one of many that squeezed light will have in the future. "With plasmonics, there is a lot of new physics to be uncovered," he says. All of which means that some of the random equipment that litters the lab might find a new use. ■



higher harmonics emerge," says Murnane, each at larger integer multiples of the original frequency. When ultrashort-pulse lasers were developed in the 1990s, Murnane and Kapteyn realized that they might be able to use them to 'pluck' an electron violently — accelerating it away from and back towards an atom of helium — and thereby generate harmonics in the form of higher-energy photons. The team succeeded in making bright ultraviolet beams[10], but it was more difficult to increase the energy while keeping the beam laser-like, with the waves emerging in synchrony.

Murnane often says that she picked physics "because it was the hardest subject" at university — an attitude that stood her in good stead with this challenge, which took 15 years to solve. The solution was to engage in what she calls "a very different way of thinking", and start not with visible-light lasers, but with longer-wavelength infrared lasers. The photons had much less energy than before. But they resonated much more strongly with the electrons in the helium atoms — in effect, giving the string a much stronger pluck — which allowed the team to combine more than 5,000 laser photons into a single X-ray photon. Theorists believed that the technique would be too inefficient to make usable beams. But by carefully tuning the helium gas so that the laser and X-rays travelled at the same speed, Murnane's team predicted, then proved, that the X-rays would emerge in step, as a bright beam[11]. "What was amazing was not just that they got the X-rays, but that they got plenty of them," says Mikhail Ivanov, a physicist at the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy in Berlin.

Murnane and Kapteyn have now made ultrafast lasers that produce X-rays of up to 1,000 electronvolts in energy, and in attosecond pulses. Although these devices do not reach the energies or brightness attained at the big free-electron laser facilities, they come close. And, at US$1 million, they are around one-thousandth of the price. The lab at JILA has eight such lasers, and discoveries in the nano-world are starting to trickle in. Murnane both builds and uses the lasers — processing the X-ray scatter patterns to capture images of charge and spin flows within materials. One counter-intuitive finding is that nanometre-sized heat sources cool quicker when packed closer together[12]. Murnane, together with collaborators including Kapteyn and Tenio Popmintchev at JILA and Andrius Baltuska at the Vienna University of Technology, is still working on refining the desktop set-up to make it even faster, more energetic and smaller. That would allow them to probe even quicker processes, deeper within materials and with higher resolution. "We're pretty optimistic we can do it," says Murnane.

After visible lasers were invented in 1960, they underwent rapid development; the same revolution is now happening for tabletop X-ray sources. Other labs around the world have developed similar approaches, says Olga Smirnova, a theorist at the Max Born Institute. But what makes the JILA technique stand out is the ability to produce such high-frequency light, with such efficiency. And then there is Murnane herself, says Smirnova: "She is really able to push the envelope of what is possible, year after year."

"She is really able to push the envelope of what is possible, year after year."

Murnane insists that they have not reached the limit yet — that higher-energy X-rays and even faster, zeptosecond (10^{-21} s) pulses may be possible. "A misconception in science sometimes is that lasers are now an old technology, and there's nothing new to learn," she says. "That's so far from the truth. ■

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