

Glass Fibre Rainbows

In their conventional form, hair-thin glass fibres ensure fast internet speeds – but conducting light with very low loss isn't the only thing they can do. **Philip Russell**, Director at the **Max Planck Institute for the Science of Light** in Erlangen, and his colleagues are using a novel type of optical fibre, known as photonic crystal fibre (PCF), to manipulate the properties of laser light and control its interactions with matter. Their work is leading to many applications, for example in advanced ultraviolet light sources and optical fibre sensors for medicine, industrial manufacturing, structural engineering and environmental monitoring.

TEXT **ROLAND WENGENMAYR**

Can you see the fibre?" asks Johannes Köhler. And there it is: a gossamer thread bridging a gap about the width of my hand. The fibre is only 100 micrometres in diameter – roughly the thickness of a human hair. Despite being so small, it has some very special characteristics; they didn't yet exist 26 years ago, so the manner in which they might guide and modify laser light was unknown. For example, intense non-linear optical effects within the fibre open up new vistas in basic research as well as promising new real-world applications. Conventional glass fibres have already fulfilled their promise – today's global fibre network forms the very backbone of our information society. Compared with the filigree fibres being developed in Erlangen, conventional glass fibres are as primitive as an early

electronic calculator next to a modern tablet computer, in the sense that PCF offers a multitude of different "apps".

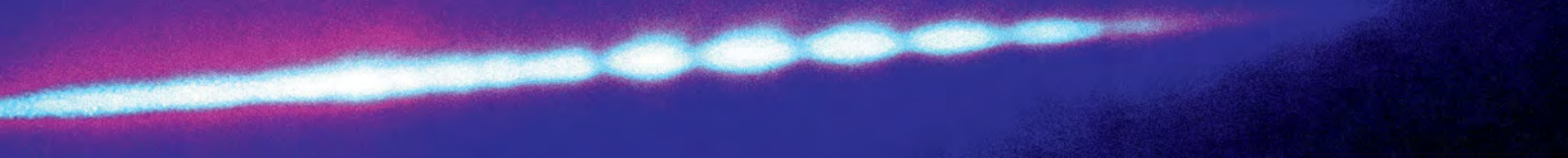
The research being pursued by Philip Russell's department at the Max Planck Institute for the Science of Light focuses on this new breed of glass fibre, which is produced by unique micro- and nano-fabrication techniques. Doctoral student Johannes Köhler and I are standing in his lab next to an optical table on which a race track for light has been set up, complete with a powerful laser, lenses, mirrors and other optical elements. The invisible infrared light of the laser is passing through the 12-centimetre-long glass fibre at which Köhler is pointing. The fibre is hollow, its interior spanned by two closely spaced parallel glass membranes that run along the entire length of the fibre.

These membranes are so gossamer-thin that the laser light, whose photons exert a weak physical force, can set them vibrating. The optoacoustic oscillations, in turn, alter the properties of the light. Just what is going on is the focus of Köhler's work. Experiments with other fibres containing different nanostructures are being conducted in nearby labs. Each alters laser light in a different way. Theodor Hänsch, Director at the Max Planck Institute of Quantum Optics in Garching, and John Hall at NIST in the US, who shared the 2005 Nobel Prize in Physics with Roy Glauber, made use of one such glass fibre type in their prize-winning work.

Philip Russell, a British physicist born in Belfast, is the pioneer of PCF and mastermind of the Erlangen-based fibre world. He directs the 40-strong

Photo: Xin Jiang

White light source: Specially prepared crystal fibres produce a broad spectrum of light from monochromatic laser pulses. This "supercontinuum" can be spread out in space using a prism at the end of the fibre. At the right-hand edge, the ultraviolet light appears as a white glow.



Photonic Crystal Fibre Science Division. "We're concerned with the interaction between light and matter," he says, describing the thrust of his research. He patiently explains the fundamental difference to conventional glass fibres, without which the high-speed internet would be inconceivable. With wry British humour, he remarks that the glass fibre has also made the spread of fake news much more efficient. He is clearly glad that, so far, his own research isn't used in communications technology.

"Glass fibres for telecommunications work like elongated, almost perfect mirrors," he explains. Such fibres have a core and a cladding consisting of two grades of glass with different refractive indices. The interface between the core and cladding therefore acts as a mirror, which reflects laser beams

back and forth inside the fibre. This is akin to throwing a Super Ball at an angle into a pipe, so that it bounces further and further into the conduit.

MARRYING GLASS FIBRES AND PHOTONIC CRYSTALS

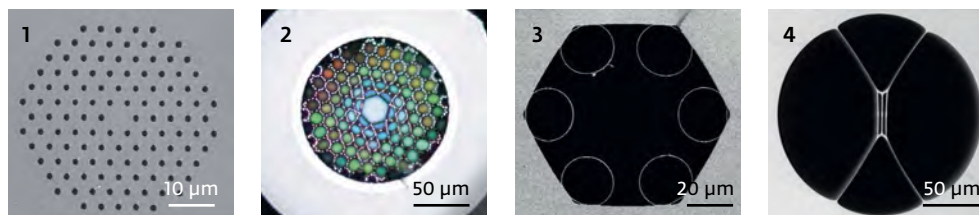
Conventional glass fibres can be understood by viewing light as rays that propagate in straight lines, bouncing off the core surface. To understand Russell's fibres, in contrast, it is necessary to also take account of the fact that light also acts like a wave.

What this means is conveyed by taking a glance at one of Russell's shelves. A glass case contains a brilliant blue morpho butterfly, which the physicist bought many years ago in an entomology museum in France. The butterfly's iridescent colours aren't created by pig-

ments but by tiny nanostructures that modify the light during reflection. The structures must have just the right spacing so that they match the wavelength of visible light: a few hundred nanometres (millionths of a millimetre).

The architectural dimensions of artificial photonic crystals are of the same order of magnitude. In one-dimensional form, such materials have important applications as antireflection coatings for mirrors, windows, spectacles and camera lenses.

In the early 1990s, Philip Russell asked himself what would happen if he combined a glass fibre with a two-dimensional photonic crystal. This should create a glass fibre with regularly spaced hollow channels running along its length, so that a cross-section of the fibre would reveal a regular pattern of holes – a photonic crystal. If their spac-



Above Researchers led by Philip Russell first produced PCFs with a solid glass core (1), which when appropriately designed could transmit light in a fundamental mode over long distances. Shortly afterwards they developed hollow-core PCFs, including a structure with a kagomé lattice (2), named after a woven bamboo pattern in Japanese Shinto shrines, which when filled with gas and driven by short laser pulses can produce ultraviolet light. Some simpler “single-ring” hollow-core fibres (3) can be used to produce a similar effect. Fibres with narrow glass membranes running over their entire length (4) are used in optoacoustic experiments. Light induces vibrations in the membranes.

Right page In a cleanroom, Michael Frosz, Xin Jiang and Philip Russell (left to right) watch the preform of a glass fibre being melted in a furnace and drawn to its final thickness.

ing is chosen appropriately – this is related to the wavelength of the laser light used – the jumps in refractive index between the air and the glass would cause strong reflection of the light in the core, preventing it from escaping through the walls of the fibre.

That was Russell’s idea. But actually realizing the first photonic crystal fibre was no easy matter. “You’ve got this dream,” Russell says, “but your courage falters in the face of difficulties.” He had to find a way to provide the already ultrafine fibres with even smaller hollow channels. Moreover, all the channels must have a defined diameter, and they must maintain the same spacing over the entire length of the fibre. “Most of my colleagues thought I was crazy,” he remarks.

Poor prospects for the young scientist who, at the time, was carrying out research at the University of Southampton. After many failures, his small team finally had a breakthrough with a technique similar to the method used for making candy floss. It exploits the fact that, at a temperature of around 1,850 degrees Celsius, quartz glass behaves very much like molten sugar. This

makes it possible to draw it into ultra-thin filaments without breaking. Equally importantly, if the glass contains an internal pattern of holes, this too shrinks as the filament is drawn, without losing its structural integrity.

FIBRES WITH COMPLETELY NEW OPTICAL PROPERTIES

After trying in vain to drill millimetre-sized holes in a thick glass rod, ready for drawing it down in size in a fibre drawing tower, Russell’s team finally came up with the idea that would prove successful. They assembled a stack of quartz glass tubes in a desired pattern and heated the stack in a furnace. They then drew the cluster of tubes down to a thin fibre. The result was the first functioning photonic crystal fibre.

Russell introduced the first photonic crystal fibre in 1996 and his team has subsequently perfected this “stack-and-draw” method. The new optical properties of the fibres soon attracted the attention of the laser world. Many research groups jumped on the idea, most notably a group at Bell Labs in Holmdel, New Jersey, who reported in

1999 that these new fibres could generate an octave-spanning frequency comb (“supercontinuum generation”), thus contributing to John Hall’s and Theodor Hänsch’s winning the Nobel Prize in Physics in 2005. A frequency comb makes it possible to measure the colours (frequencies) of light with unprecedented precision, and thus to construct optical clocks that are a thousand times more accurate than their conventional counterparts. This will make satellite-based global positioning systems even more accurate in the future. “We were just about ‘there’ in 1999,” Russell sighs, “but we didn’t have the necessary equipment at the University of Bath, so weren’t the first to discover supercontinuum generation in PCF.”

What exactly happens to light in such fibres depends on the internal microstructure. In simple terms, light waves are trapped inside the fibres rather like sound waves in a resonating musical instrument. Russell, himself an accomplished amateur pianist, takes the kettle drum as an example. When struck, the drum-skin begins to oscillate at its fundamental frequency, which carries



the deepest tone of the instrument. At the same time, it can emit many higher-frequency harmonics. Laser light in a photonic crystal fibre acts in a similar manner. In a PCF with a solid glass core, the surrounding triangular pattern of hollow channels acts as an excellent filter. It filters out all the harmonics so that the light in the core vibrates only at the fundamental frequency.

The light waves may be viewed as being “stretched” across the core, in analogy with sound waves on the skin of a drum. “For the fundamental mode of the “drum”, the hollow channels act like the bars of a jail cell,” Russell says, “trapping the light.” In contrast, harmonics of the “drum skin” are able to escape between the bars. A pure fundamental mode can therefore be transmitted over very long distances, without any contamination from higher-order modes. “This endlessly single-mode behaviour was an unexpected discovery,” says Russell, and the paper first reporting it is now the most highly cited in the field.

Hollow-core PCF introduced an exciting new feature: the ability to prevent, for the first time, the spreading

out, or blooming, of laser beams as they travel through free space, diminishing the intensity of the light. As a result, laser light can be kept narrowly focused in a single-lobed fundamental mode over long distances. When the fibre is filled with gas, possible huge enhancements in nonlinear light-gas interactions become possible, as we shall see.

Over the past two and a half decades, Russell’s team – since 2009 at the Max Planck Institute for the Science of Light – has developed a wide array of glass-fibre structures. At the Institute, Xin Jiang leads me to the sanctum sanctorum, a multi-storey cleanroom that houses the fibre-drawing towers. Because the fibre blanks are sensitive to dust, we can only peer at them through a window pane.

A METHOD THAT WORKS LIKE A PASTA MACHINE

The researchers in Erlangen fashion their glass fibres in two steps, explains Michael Frosz, head of the team responsible for producing them. First, they assemble a stack of prefabricated glass tubes into a desired pattern, heat it,

fuse it together and stretch it to form a preform cane that is just a few millimetres thick. They then clamp the cane at the top of the fibre-drawing tower, which reaches a height of about eight metres. A compact, tubular graphite furnace melts the preform. Then the lower end of the preform is drawn into a hair-thin filament. A protective plastic sheath is added, and the finished fibre is rolled up onto a spool.

Beyond this standard procedure, Russell’s team is developing a second method: extrusion. “In principle, it works like a pasta machine,” says Xin Jiang, the manager of the “glass studio.” A pasta machine presses dough through a disc pierced by holes. In a similar manner, a hot mass of glass is pressed through a perforated disc. By appropriate choice of hole pattern, almost any structure can be imparted to the fibre blank, which is subsequently drawn into a thin filament. “That gives us a lot of design scope,” Russell says.

Three basic types of glass fibres can be distinguished. One type features such structures as thin glass membranes. Another has a glass-filled core through which light passes, surround-



ed by an array of narrow hollow channels: the photonic crystal. The third type has a hollow core within which the light is guided.

The Erlangen-based researchers use hollow-core fibres to manipulate microparticles with laser light inside the core. “We use photonic forces in the same way as they are used in a technique known as optical tweezers,” explains team leader Shangran Xie. He and his team have developed a system that uses a light-trapped particle as a sensor for electric fields. Colleagues at the Jülich Research Centre have expressed interest in using this sensor to measure electrical fields in a high-voltage particle accelerator that people are not allowed to enter during operation.

Because the sensors, incorporated in photonic crystal fibres hundreds of metres long, can be used in locations that are too dangerous for human access, they have potential applications in nuclear power plants. These “flying particle” sensors could be used to measure radioactivity levels and can even be switched to respond to different types of radiation.

At the same time, the physicists in Erlangen have been pursuing a new idea. A liquid-filled hollow-core PCF is suitable for examining living cells, al-

lowing light to be used, for example, to trap and propel a single cancer cell inside the core. A fluid containing a new drug could then be pumped through the fibre to test how the cell reacts. This represents an innovative approach to pharmaceutical research on individual cells.

However, the main area of research in Erlangen is nonlinear optics, specifically nonlinear wavelength conversion. This field exploits the ability of photonic crystal fibres to alter the colour of laser light. For example, a solid-core fibre produces the famous frequency comb mentioned above. Gas-filled, hollow-core fibres are currently a key area of research in Erlangen. The scientists fire powerful, ultra-short laser pulses into one end of such fibres, and light with transformed properties emerges from the other end.

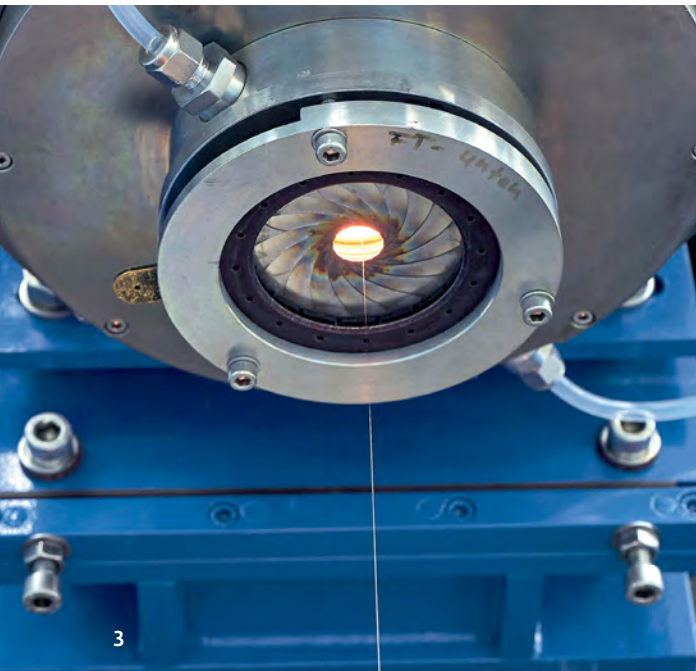
OF SPECIAL INTEREST: ULTRAVIOLET LASER LIGHT

Russell compares the complex processes that take place inside the fibre with what an amplifier does to the signal from an electric guitar in rock music. As long as the amplifier is set to a moderate level, it amplifies the wave without distorting it. The gain is said to be linear. A rock guitarist, on the other

hand, jacks up the amplification so high that the signal is distorted. This produces overtones that give the rock guitar its typical sound. In this case, the gain is said to be nonlinear, because it changes the waveform of the incoming signal.

That is more or less how photonic crystal fibres work. The team of Francesco Tani, a postdoc from Italy, is taking nonlinearity a step further. The fibres they are using are filled with a noble gas, such as argon or neon. The wavelengths of light from powerful infrared laser pulses fan out like a rainbow, with frequencies that can be tuned by varying the gas pressure in the fibre, enabling the colour of the light to be controlled. Ultraviolet laser light generated in this way has numerous applications in research and technology.

In fact, strong ultraviolet light can be produced so reliably with photonic crystal fibres that a start-up company at the institute intends to commercialize the process. The company, ultralumina, was founded in Erlangen in 2016. It has a staff of six and already has interested customers lining up. Companies in the semiconductor industry would like to use the ultraviolet light in their inspection systems. “To check the quality of structures on silicon wafers, electronic



chip manufacturers require very bright shortwave light,” says technical manager Patrick Uebel. The new light source may also find applications in microscopy. “The first financial year was very good,” his colleague Sebastian Bauerschmidt reports.

Photonic crystal fibres could even be used to construct compact sources of X-ray laser light. Current sources either involve free-electron lasers – huge, expensive electron accelerators – or high harmonic generation in noble gases using very short pulses with multi-milli-Joule energies. Gas-filled PCF could be the key to generating X-rays from ultrashort pulses with energies 1,000 times less, in a convenient tabletop system, for use in materials research, medicine and technology.

It would take a book to describe the broad range of activities being pursued in Erlangen – a “bible” of the photonic crystal fibre world, as it were. And the fibres also have a spiritual side, at least according to Google, which recognizes Russell’s fibres as sacred. In his first presentations, the physicist used the term “holey fibre” to emphasize the perforation of the fibres. Visibly amused, Russell describes how a typo on the internet changed the term to “holy fibres”. ◀

From production to experiment: A researcher in Erlangen stacks a preform of hollow capillaries and rods to form the starting structure – the preform – for a photonic crystal fibre (1). Philip Russell (2) proposed photonic crystal fibres in the early 1990s. The preforms are melted in a furnace, after which they are drawn into fibre about as thin as a human hair (3). Using gas-filled hollow-core PCF, Francesco Tani is able to produce a wide range of laser wavelengths, starting with invisible infrared laser pulses (4).

TO THE POINT

- In photonic crystal fibre (PCF), Philip Russell has developed an optical fibre with a periodic lattice of microscopic hollow channels running along its entire length.
- Hollow-core PCFs can maintain laser light in a tight focus over very long distances, limited only by the loss of the fibre. Nonlinear optical effects in gases can thus be greatly enhanced by filling the fibre with gas.
- PCFs can be designed to generate new colours of light, including light in the ultra-violet range, from commonly available lasers. Other types of PCF can be used as versatile optical-fibre based sensors of multiple quantities, such as electric field, temperature, twist and radiation levels.

GLOSSARY

The **fundamental mode** of light in a fibre core has a close analogy in the fundamental tone of a drum skin when the whole skin oscillates to and fro in the same direction. Higher-order modes (“harmonics”) have sub-regions that move in opposite directions. Like a drum skin, most fibre cores support multiple harmonics.

Photonic crystal: A material whose optical properties are altered by a periodic structure, such as regularly arranged air-filled channels. Light can be selectively reflected at such structures according to its colour (wavelength). This phenomenon explains the iridescent colours of many butterfly wings.

Photonic crystal fibre: A glass fibre in which an array of microscopic hollow channels is arranged around a central hollow or solid core. This cladding structure can be used to control the light travelling through the fibre in diverse ways.