Maryanne Large, Alex Argyros and Martijn van Eijkelenborg have developed a way to make cheaper polymer optical fibres that are competitive with silica but cheaper to produce.

Light on a Leash:

Reinventing Optical Fibres

Maryanne Large explains how light can be guided through air cores, opening the way to use polymer optical fibres that are cheaper and easier to use.

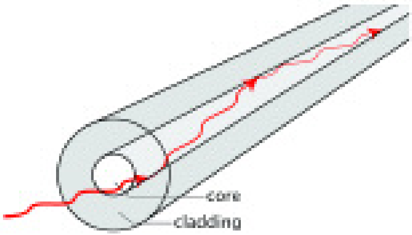

Figure 1. Optical fibres are pipes for light. Light is confined to the central "core", which is surrounded by a reflecting interface. The outer region of the fibre is called the "cladding". Image: Steven Manos, OFTC

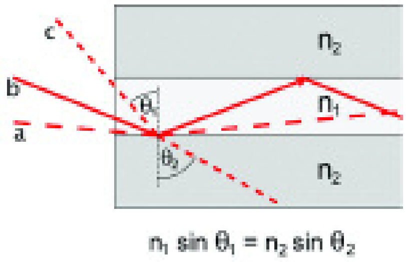

Figure 2. Snell's law relates the input angle of the light θ_1, the refractive indices of the materials n_1 and n_2 to the propagation angle of the refracted light, θ_2. If the incident angle is in the correct range, the interface between the two materials can act as a mirror, trapping the light in the high index material. Image: Steven Manos, OFTC

Optical fibres are essentially "pipes" for light. They confine light inside a "core" so that light, that most ethereal of things, can be directed in a very controlled way to where it is needed. Depending on the application, this could mean transmission over thousands of kilometres in undersea cables; gathering the faint signals from a star to the detection system of a telescope; or even sending light inside the human body for imaging or laser surgery.

The most familiar way of controlling the direction of light is with a mirror. Indeed, a naive view of an optical fibre is that the core region is surrounded by a "mirror" surface so that light, once it enters the core, has no means of escaping except to travel along the length of the fibre.

Metallic reflection can be used in this way, but it is very uncommon because all metallic surfaces absorb some of the light that falls upon them. This isn't a problem for most applications, but the length and size of the optical fibres means that the small losses at each reflection rapidly accumulate and become unworkable. The central mystery of all optical fibres is therefore how best to make a mirror from a completely transparent material.

The conventional way of doing this is to use total internal reflection. When light travels from one transparent medium to another, it changes direction in a way that is determined by an equation called Snell's law (Fig. 2).

This simple relationship implies something unusual: for a range of angles, when light travels from high refractive index material to a lower index material the interface between the two surfaces begins to act as a mirror, reflecting the light back into the high refractive index material. This phenomenon is the basis for almost all optical fibres, and by definition it implies that the refractive index of the core is higher than the refractive index of the "cladding" region surrounding it.

By any measure, conventional optical fibres have been an incredibly successful technology, but they do have limitations. In telecommunications, for example, the sheer volume and speed of information transmitted means that fibres are increasingly being pushed to their limits. Glass is a dispersive material, so light of slightly different wavelengths will travel at slightly different speeds down the fibre, blurring the signals; light can itself slightly modify the optical properties of the glass in a way that depends on its intensity; and there are some useful wavelengths (particularly in the mid infra-red range) where glass is not very transparent.

The ideal medium in which to guide light is actually air but, given its refractive index, total internal reflection in air is impossible. But can we make a fibre that guides light in air?

Physicists know that the interaction of light with matter is actually quite weak. Most photons gad about the universe without interacting very much with anything at all, so controlling them isn't easy.

Total internal reflection is one way to manipulate light, but it's long been known that there is another: periodicity. As light is itself a periodic wave phenomenon, structures that have similar size or periodicity to the wavelength of light can dramatically affect its propagation.

The most familiar example of this occurs when a film of soap or oil becomes very thin, and looks slightly coloured because of constructive interference between the light reflected from the front and back surfaces (Fig. 3). This is quite a weak effect for a single thin film, but we can make it stronger by adding similar surfaces and arranging them appropriately into a stack. These stacks can give very strong reflections but only of particular wavelength regions, where the periodicity of the stack matches that of the light.

In modern terminology, these wavelength regions are called "photonic bandgaps". The "bandgaps" refer to the wavelength bands that cannot travel through the stack and are therefore reflected.

Multilayer stacks have long been used in optics to produce well-defined optical effects such as mirrors, filters or lens coatings. What has been less obvious is that it is possible to use a similar process to make an optical fibre that guides light in air.

The first air-guiding fibres were made in silica glass in 1999 by the University of Bath in the UK (Fig. 4). It is no exaggeration to say that they caused a scientific storm, not only because they were so counter-intuitive but also because they opened up whole new applications.

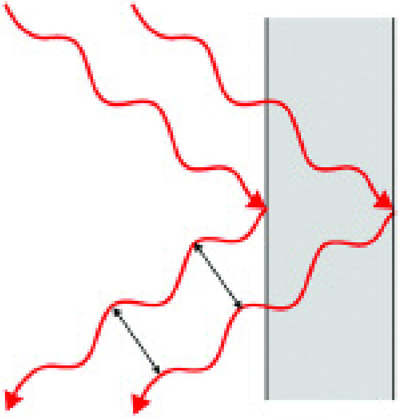

Figure 3. When a thin film has dimensions comparable with that of the wavelength of light it produces a coloured reflection due to interference between the light reflected from the front and back surfaces. Here, the peaks of the two reflections coincide (i.e. the light is in phase), so the interference is constructive. Image: Steven Manos, OFTC

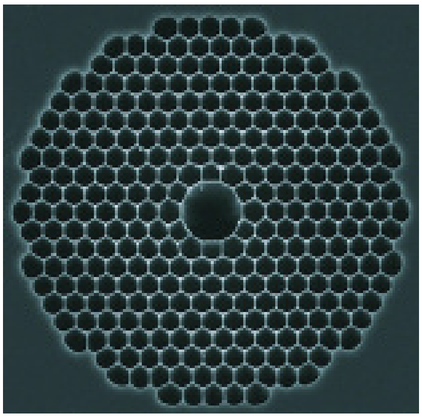

Figure 4. A silica hollow core fibre. The core is about 10 μm in diameter.
Image: University of Bath.

For example, there are many applications for which we would like to guide light in a low refractive index material, such as water or a gas. This is now possible. Very sensitive detection of gases or biomolecules are some of the potential implications.

It is also possible to do something even stranger: make an optical fibre out of a non-transparent material.

Light in a hollow core fibre is mostly travelling in the air. Only a few per cent, and potentially even less, travels in the solid material. This means that the properties of the solid material are suddenly much less important.

This is attractive because it allows us to make fibres for some of the "problem" wavelengths mentioned earlier. It also makes it possible to more easily transport the very high intensities of light that are needed for many industrial processing applications and surgery. These high intensities always need to be treated with care because they can damage the material used to make the fibre. When the vast majority of the light is in air, this becomes a much less compelling issue.

But from our point of view the most profound advantage of hollow core fibres is that you can make them of optically inferior materials and get away with it.

Plastic optical fibres have long been regarded as a slightly feeble sibling of silica fibres. Although plastics are cheap, easily processed, lighter and more mechanically robust than silica, they are also much less transparent, and transparency is pretty much the bottom line for conventional optical fibres. Without the extraordinary transparency of silica, plastic fibres have been confined to niche applications such as very short distance high data rate fibres, where the mechanical advantages and ease of connection outweigh the lower optical performance.

Hollow core fibres shift the balance back a bit. In principle they are "material-agnostic". The only material that really matters is that in the hollow core, so plastic fibres now have the chance to compete directly with silica fibres for the first time. And they bring with them some very real advantages.

Hollow core fibres are incredibly difficult to fabricate. In fact, despite an extensive global effort, only three groups have succeeded in doing so. They are hard to make for several reasons: the air fraction of the fibre needs to be very high (90% or more) and the regularity of the periodic structure is critical to its success.

In silica, these fibres are essentially handmade. First, a bigger, fatter form of the fibre called a "preform" is made by carefully stacking capillaries 1–2 mm thick into an outer tube, and then the central capillary is removed to define the space that will become the hollow core. The preform is then mounted in a draw tower (Fig. 5), where it is heated to over 2000°C and pulled into a fibre. The transformation of preform to fibre is therefore delicate, performed under extreme conditions, and painfully easy to get wrong.

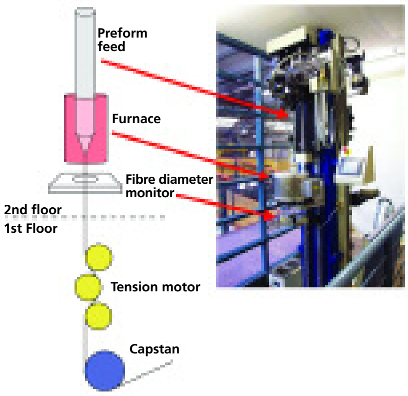

Figure 5. A schematic of a fibre draw tower, together with a photograph of the new polymer draw tower used at the OFTC. The preform is fed into a furnace where it is heated to a sufficiently high temperature and pulled out into a fibre. The tension and fibre diameter are monitored, and feedback control is used to ensure that the fibre remains uniform for the whole draw.

Image: Steven Manos, OFTC

By contrast, plastics are much more forgiving. The technology of processing plastics is vast, allowing a range of techniques to be used to make the preforms, including casting, moulding and extrusion as well as the prototyping technique we most commonly use – simply drilling the required pattern of holes. Most of these techniques have now been successfully demonstrated in making plastic preforms.

It is also possible to produce preforms by stacking capillaries, and these capillaries can be made much larger than 1–2 mm in diameter. Figure 6 shows a photograph of a plastic air core preform (8 cm in diameter) compared with a similar one made in silica. Thus, plastics have brought the prospect of a cheap mass production technology to a previously gourmet fibre.

This is all very well in practice, but we still need to make the fibre from the preform. There is still a lot of work to be done, but the preliminary evidence is that making the fibre from the preform may also be easier.

This might seem a strange statement from someone who has spent 4 years trying to make hollow core plastic fibres, but those years can perhaps best be put in context by Figure 7, which shows the original "draw tower" we used in 2001. The intervening years saw us redesign and make new draw towers in-house, but it was only at the end of 2004 that we finally commissioned a commercial draw tower (Fig. 8).

The new tower has numerous advantages over the previous versions. The critical advantages are that it uses radiative heating, which allows very large preforms with very high air fractions to be more efficiently and uniformly heated. The new tower also allows the holes to be pressurised and has much better process control, so the uniformity of the fibres is vastly improved.

After some years of trying, we made the first hollow core plastic fibres just a few months after commissioning the tower. This is the first time that a hollow core fibre has ever been made in a material other than silica, and only the fourth time that anyone has succeeded in making these fibres. The results are not yet spectacular in terms of loss of light during transmission, but we are rapidly improving our fabrication techniques and have already

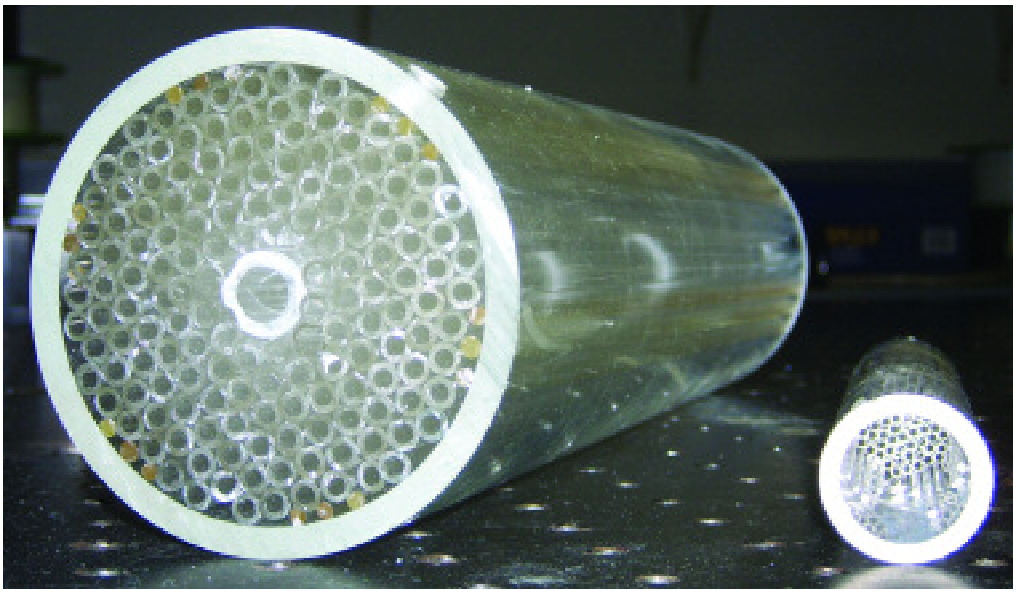

Figure 6. A comparison of a polymer fibre preform (left) and a silica preform for a similar structure. The polymer preform can produce an estimated length of 300 km from a single draw. The current world record for silica photonic crystal fibre is 100 km.

Image: Alex Argyros, OFTC

Figure 7. Alex Argyros draws one of our first plastic fibres by hand using a furnace borrowed from another group. Image: J. Zagari

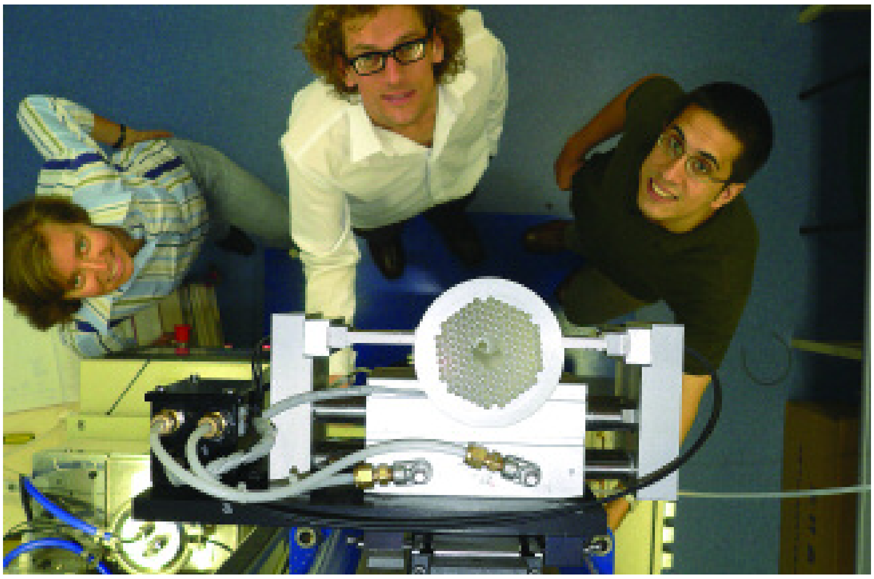

Figure 8. Maryanne Large, Martijn van Eijkelenborg and Alex Argyros with the recently commissioned draw tower for plastic fibres. A hollow core preform is shown, ready for drawing. Image: J. Digweed

shown that the very large preform shown in Figure 6 can be successfully drawn down.

These "proof-of-concept" results need to be further developed for the technology, and for the science, to move forward. We need to dramatically improve the transmission performance and show that we can make the fibres consistently and in high volumes.

We now have both the experimental results and theoretical understanding to know that these are not intractable problems. They will, however, require the most essential ingredients of scientific progress: patience, creativity and cash.

Clearly, addressing these issues are some of the tasks that we have set ourselves in the coming months, but that is by no means all. One of the nicest features about having a process that is at least an order of magnitude cheaper than that of silica, as well as a fabrication technique that makes it much easier to make very diverse structures, is that we have the chance to be more playful in our designs. If we try making a new type of fibre, and it doesn't work as we hoped, then mostly all we have lost is a bit of time. This allows us to use our fibres as a kind of photonic crystal sandpit, testing out new ideas and pushing the boundaries of optical fibre design.

One of the ideas we are working with in this context is to develop a hollow core fibre that guides light without polarisation problems. Polarisation is an unwanted feature of light in many applications because small defects and asymmetries in the fibre can easily make it "birefringent". This literally means that there are two refractive indices rather than one – light with its electric field in the x direction experiences a different refractive index than light with its electric field in the y direction, and therefore the two travel at different speeds. This is a major limitation to the performance of fibres in telecommunication systems.

We are trying to get around the problem by making a fibre that only guides light with one type of polarisation. We are doing this by using a technique many readers may be familiar with: the Brewster condition. This condition says that when you have an interface between two transparent materials of different refractive indices, there is a special angle at which all the reflected light is polarised with its electric field parallel to the interfaces. In an optical fibre we are only interested in light that is reflected by the interfaces as this is the only light that is guided by the fibre, and so it is possible to use this effect to produce a fibre that is free of birefringence problems.

It would take much more than this short article to explain all the other possibilities, but these are some that we are exploring:

- filling up the holes with solutions containing biological molecules to see if can develop more sensitive sensors;
- working with the Australian National University to develop fibres that guide atoms down the hollow core;
- making fibres for very long wavelength radiation, such as microwaves; and
- improving and extending the performance of hollow core fibres to lower the loss of light and perhaps to extend the bandgap regions.

We have certainly made a lot of progress, but there is still far more work to be done.

Maryanne Large is an Australian Research Fellow and Deputy Director of the University of Sydney's Optical Fibre Technology Centre, and shared the 2005 *Australasian Science* Prize with co-workers Alex Argyros and Martijn van Eijkelenborg.