Leading lights

High prestige in science generally goes to grand theories — the bold, imaginative schemes that wrap up the laws of nature in precise mathematical terms. We revere the elegance of general relativity or quantum theory, or the explanatory power of plate tectonics or the theory of evolution. Acclaim also goes to less fundamental theories — for the various mechanisms leading to dynamical chaos, for example, or the transition to turbulence in fluids.

Yet for all the prestige, science more routinely runs on haphazard tinkering in the lab, on making new designs or structures, or putting materials together in different ways. Experiments sometimes turn up things that work even if no one knows quite why, and such discoveries can have repercussions even for the grand theories. One prominent example: key to the 2015 LIGO detection of gravitational waves was decades of slow advancement of the design and control of lasers.

Another recent example of progress through tinkering comes in fibre-optic technology. An engineer named Elias Snitzer published the first theoretical description of a fibre-optic cable back in 1961, envisioning a glass fibre that would guide light by total internal reflection, and have an inner core small enough that it would carry only a single waveguide mode. Telephone companies by the late 1970s were relaying signals extensively with fibre optics and, naively, I thought until recently that today's fibre technology still followed the same basic idea.

But this technology has advanced through a blizzard of innovations, many introduced without much theoretical motivation. A fundamental change was the introduction of tiny hollow tubes running within the fibre, which can be filled with air, or with a variety of materials ranging from liquids or liquid crystals to metals or gases, which interact with propagating light. In so doing, researchers have discovered a host of ways to exert ever more delicate control on light (C. Markos *et al.*, *Rev. Mod. Phys.* **89,** 045003; 2017).

The main pathway to better fibres has been to forego total internal reflection, and find other ways to engineer light confinement. Early research pursued the idea of photonic crystals — fibre structures engineered to have transverse periodic modulations of their index of refraction. As in quantum solids, such periodicity creates a band structure of allowed wave states and bandgaps of forbidden frequencies. In the 1990s, researchers chasing this idea experimented with a variety of fibres with arrays of hollow tubes running parallel to the axis. As it turned out, most didn't technically behave as photonic crystals. But many did carry light effectively for other reasons.

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Hence, as a quirk of history, technologically useful structures of this kind now go by the name of photonic crystal fibres, even though the name only sometimes applies. A breakthrough came in 1999 with the demonstration of a real bandgap effect in a hollow-core crystal fibre filled with air, and the subsequent proof, in 2002, that strong nonlinear optical effects could be realized in a hollow-core fibre filled with pressurized hydrogen gas.

Many other variations now exist, with multiple possible guidance mechanisms, all surprisingly still open to debate. In some fibres, as Markos and colleagues note, it seems that a lack of coupling between the transverse field modes in the fibre core and cladding acts to trap the light. In other cases, researchers instead think that the cladding structure acts as a highly reflective mirror-like enclosing surface due to an 'anti-resonance' mechanism, in which destructive interference suppresses light refraction and escape into the cladding layers. Intricate structures are not required to guide light with minimal loss, as a honeycomb lattice or even a single annular layer of tubes works as well.

But the real excitement of modern optical fibres arises when those internal tubular structures get filled with other materials able to interact with laser light in specific ways. For example, a simple liquid of high refractive index placed into the air holes can act to tune the optical properties of the fibre. The value of the index, and the geometry of the holes, determines the nature and location of the fibre's bandgaps. Because the refractive index depends on temperature, these gaps can be tuned through changes in temperature. This allows simple fibres that transmit light to evolve into more active elements such as optical switches or tunable bandpass filters.

Or, rather than ordinary liquids, how about liquid crystals? Liquid crystals possess orientational order, or a preferred direction in space, which can often be changed by application of an electric field. This allows much faster and more detailed control of a fibre's optical properties. For example, researchers have used this idea to fashion fibres that act as electrically controlled broadband polarizers, for which the optical axis of the polarizer is easily adjusted in steps of 45°. With other clever choices of liquid crystals, they've made variable wave plates. Replace liquid crystals with magnetic liquids, such as ferrofluids, and you get fibres that can be controlled by magnetic fields — and so able to act as delicate optical sensors of magnetic fields.

Replacing these liquids with atomic or molecular gases opens up another world of possibilities. Fibres containing gases allow sensitive experiments in quantum optics, for several reasons. Compared with any set-up that focuses light to interact with matter, a waveguide fibre geometry greatly increases the light–matter interaction, reflected in the product of light intensity and interaction length. This permits experimental probes even of extremely weak nonlinear processes.

These nonlinear effects make it possible to create new and useful forms of light. For example, appropriate nonlinearities make intense laser pulses compress themselves as they travel, allowing the engineering of ultrafast pulses as short as 5 fs at some wavelengths. This technology has important applications, such as fast spectroscopy of molecular systems, which requires intense ulrashort pulses as specific frequencies.

Nonlinearity also allows the propagation of coherent solitons that maintain their precise shape as they propagate. Hollow-core technology has opened another road to new physics, as soliton pulses, if intense enough, will ionize some of the hollow-core gas, leading to complex plasma–soliton interactions.

All this from the systematic exploration of how light can be manipulated when guided within carefully manufactured silica fibres. We often think of science as the driver of new technologies. In this case, however, it's often the other way around — the new technology leads the way, and the new science comes later. ❐

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