OPTICAL FIBRES

Beyond the diffraction limit

By adding a tiny hole into the solid-core of a photonic-crystal fibre, scientists have been able to beat the diffraction limit and confine and guide light in the subwavelength regime.

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Optical fibres are well established as the medium of choice for confining light over long distances. The range of optical properties that can be realized in fibre form has increased dramatically over the past decade thanks to the development of microstructured optical fibres[1]. These fibres typically contain micrometre-scale air holes that run the length of the fibre. There is great interest in developing classes of optical fibres that confine light strongly in order to produce high light intensities. Such fibres have a broad range of important applications including optical data processing and broadband supercontinuum sources. However, in both conventional telecommunications fibres and microstructured fibres, once the core is significantly smaller than the wavelength of light, light spreads out into the surrounding cladding medium, which fundamentally limits the light intensities that can be achieved. The class of fibres presented on page 115 of this issue by Wiederhecker *et al.*[2] offer a powerful approach to achieving tightly confined (subwavelength) guidance of light.

At any interface between two materials within a fibre cross-section, there is an increase in the electric-field strength on the low-refractive-index side. Within most microstructured fibres investigated until now, the light intensity at the air–glass boundaries is low relative to the peak intensity in the core, as the air holes are typically located in the tails of the mode field distribution. For this reason, the enhancement in the electric-field strength at the air–glass boundaries, although it can be noticeable, does not usually lead to the generation of intensities higher than the peak intensity in the centre of the core.

Consider now the introduction of a subwavelength (in this case 100–200 nm) air hole into the fibre core, right in the peak of the intensity distribution. This leads to a significant local intensity enhancement. Owing to the small size of this central air hole, the decay of the evanescent light within the hole is minimal, and so enhanced field intensities are achieved throughout the hole. In essence, light is concentrated within the subwavelength hole (Fig. 1).

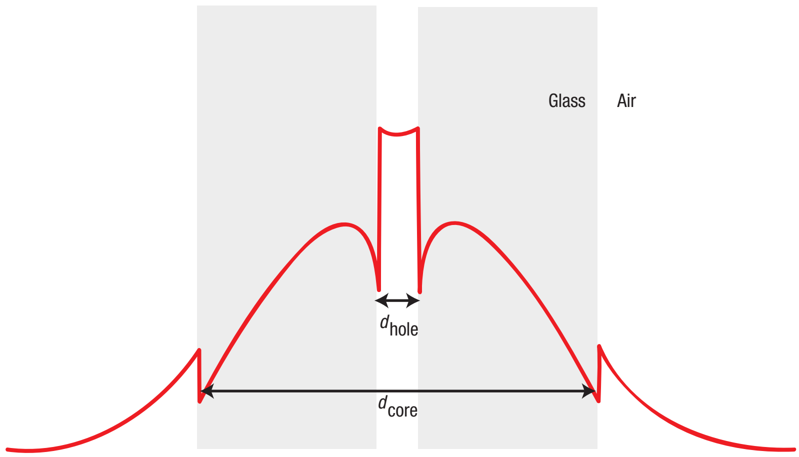

Figure 1 Schematic of how the magnitude of the electric field (red line) changes across the cross-section of the fibre. Calculations are performed for a central hollow bore diameter (d_{hole}) of 100 nm and a solid core diameter (d_{core}) of 1 μm.

The production of fibres with such small holes is technologically challenging, and as Wiederhecker *et al.* demonstrate, the capillary stacking technique that is routinely used for the fabrication of silica microstructured fibres is particularly well-suited to this challenge. In this work, the microstructured fibre itself effectively acts as a host for the small air hole, and the other air holes simply act to form a cladding with a low effective refractive index, thus producing a fibre with a large numerical aperture that can generate high light intensities within the fibre core. Although a similar effect could be achieved using a conventional solid-fibre design with a small central hole, such a fibre would actually be more difficult to manufacture than the more complex microstructured fibre.

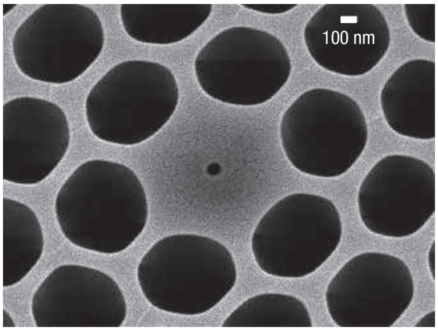

Figure 2 Scanning-electron-microscope image of the end of a photonic-crystal fibre containing a subwavelength bore, fabricated by Wiederhecker *et al.*[2]

One tantalizing feature of these fibres is the fact that the region of enhanced intensity occurs within air, which opens up the prospect of using these holes as sites for interacting intense light with materials located within the air void. Fibres also provide long interaction lengths, and this combination of properties makes this class of fibres attractive for gas and liquid sensing, atomic waveguides and forming cavities with small modal volumes, to name a few potential applications. It is worth noting that the small holes required to produce field confinement will in practice seriously limit the opportunities for filling the void with liquids and gases within a reasonable time scale. However, innovative modifications to the fibre cross-section may possibly mitigate this problem.

The use of small holes in or near the core of an optical fibre is a well-known means of tailoring the dispersion. One of the most attractive features of microstructured fibres is the diverse dispersion characteristics they can exhibit (see for example ref. 3). The use of additional small holes will probably extend still further the range of achievable dispersion properties.

The fibres reported by Wiederhecker *et al.* (Fig. 2) have losses of the order of a few dB m^{-1}. Although it may be possible to reduce this somewhat, the electric field is enhanced at the air–glass boundaries and so it is to be expected that surface imperfections will significantly contribute to the loss. Hence loss is always likely to limit the useful length of this class of fibres.

The magnitude of the electric-field enhancement that occurs at the air–glass boundaries is determined by the ratio of the dielectric constants. By moving beyond silica to higher-index (soft) glasses such as tellurites and chalcogenides, it will be possible to enhance the field intensities within these fibres by up to a factor of two. A broad range of microstructured fibres can now be produced in soft glasses[4].

The enhancement of the electric field within tiny holes is more than just a tool for increasing the light intensity. It is also an effective and practical way of localizing light on previously inaccessible spatial scales. Indeed, the only limitation on the feature size that can be achieved is dictated by the degree of precision with which the fibre fabrication conditions can be specified and controlled.

Subwavelength localization has the potential to lead to a range of possible applications including imaging systems with improved spatial resolution and even the selective excitation or detection of matter on the molecular scale. Fibres with arrays of small holes could be used as a means of patterning light on a subwavelength scale. The application of such future fibres is only limited by the imagination.

References

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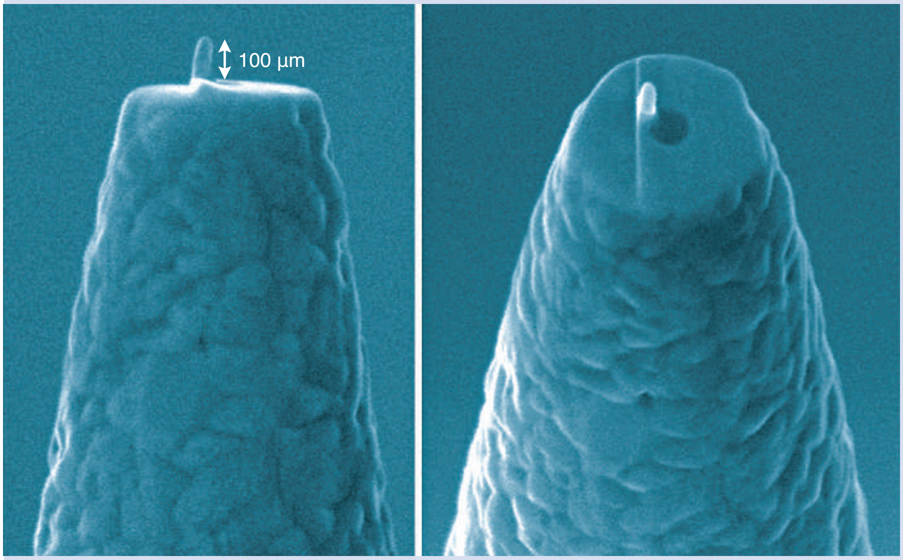
OPTICAL ANTENNAS

Nano-antenna picks up green light



By bombarding the tip of a tapered optical fibre with ions, European scientists have succeeded in crafting a nano-antenna that operates at optical wavelengths and can efficiently 'pick-up' green light (*Nano Lett.* **7,** 28–33; 2006). Such optical antennas may ultimately prove useful for subwavelength microscopy and integrated optoelectronic devices, but, for now, they show how a well-known object can be reduced to the nanoscale to create fascinating tools for the future.

Wireless technology literally surrounds us with information, and the concept of the antenna has a crucial role to play. By converting free-space electromagnetic fields into guided waves, or vice versa, antennas act as either receivers or transmitters. The wavelength at which antennas operate is intrinsically related to their size and shape: for a simple antenna, the height required is approximately one quarter of the wavelength.

For an antenna to operate in the optical regime, its dimensions must be on the 100-nm scale. This has now been achieved by scientists in Spain and The Netherlands.

Starting with the flat end of a single-mode optical fibre, Tim Taminiau and colleagues create a sharp glass tip by so-called heat-pulling — applying tension to hot, soft glass. This tip is coated with a 150-nm-thick layer of aluminium and is then shaped by bombarding it with high-velocity ions. The result is a nano-antenna that is just 50 nm in diameter and has a height of between 30 and 140 nm. By positioning it on the edge of an aperture into the optical fibre, the local field effectively drives the antenna, replacing the transmission lines in the radio-wave equivalent. Simulations of the fields around the structure show that it behaves in the same way as a standard radio-frequency monopole antenna, enhancing the localized field near the apex at a resonant wavelength dependent on the height: a 75-nm tall antenna is resonant with green light with a wavelength of 514 nm. The device could also act as a receiver when driven by far-field illumination.

To demonstrate the potential of their antenna, the team have used it to perform near-field scanning optical microscopy on fluorescent molecules suspended in a polymer film. Laser light at 514 nm is passed along the optical fibre to excite molecules and the fluorescence is collected in the same way. The sample is scanned beneath the antenna to produce a two-dimensional image and it is here that the effect of the antenna can be seen. The molecules can be resolved with a resolution of 26 nm, three times smaller than the patterns associated with the aperture. This result demonstrates the tight confinement of the enhanced field at the end of the antenna.

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