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Microstructured Polymer Optical Fibres: New Opportunities and Challenges

Maryanne C. J. Large^{a b}, A. Argyros^{a b}, F. Cox^{a b},
M. A. van Eijkelenborg^{a b}, S. Ponrathnam^c, N. S.
Pujari^c, I. M. Bassett^a, R. Lwin^{a d} & G. W. Barton^{a d}

^a Optical Fibre Technology Centre, University of Sydney APCRC, Australia

^b School of Physics, University of Sydney, Australia

^c Polymer Science and Engineering group, Chemical Engineering and Process Development Division, National Chemical Laboratory, India

^d Department of Chemical Engineering, Australia

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Maryanne C. J. Large

A. Argyros

F. Cox

M. A. van Eijkelenborg

Optical Fibre Technology Centre, University of Sydney APCRC,
Australia and School of Physics, University of Sydney, Australia

S. Ponrathnam

N. S. Pujari

Polymer Science and Engineering group, Chemical Engineering and
Process Development Division, National Chemical Laboratory, India

I. M. Bassett

Optical Fibre Technology Centre, University of Sydney APCRC,
Australia

R. Lwin

G. W. Barton

Optical Fibre Technology Centre, University of Sydney APCRC,
Australia and Department of Chemical Engineering, Australia

Microstructured polymer optical fibres [mPOF] were first developed in 2001, and have attracted attention in part because the range of fabrication techniques possible with polymers has allowed novel structures to be made that cannot be made simply in other materials. Their material properties also offer attractive possibilities as polymers can contain a much larger variety of dopants than glass. In this article, we review progress on some of the major challenges of this technology: particularly the need to reduce fibre losses, and report on some recent developments including the fabrication of the first hollow core mPOF. Some initial investigations into changing the material properties are reviewed.

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Address correspondence to Maryanne C. J. Large, Optical Fibre Technology Centre, University of Sydney APCRC, NSW 1430, Australia. E-mail: m.large@oftec.usyd.edu.au.

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INTRODUCTION

Guidance of light requires a variation in refractive index, which in conventional optical fibres is achieved either by chemical doping, or by the use of more than one material. Microstructured optical fibres [MOFs], also known as “photonic crystal” [PCF] or “holey” fibres, achieve light guidance through a patterning of tiny holes which run along the entire length of the fibre, as shown in Figure 1. In the simplest case, where the core of the fibre is solid, MOFs can be thought of as using holes to “dope” the material with air, and thus lower its effective refractive index. Using the holes to modify the material in this way, it is straightforward to produce what is effectively a step index fibre, or indeed any other refractive index profile. This might suggest that MOFs are not very different from conventional fibres, but the reality is much more interesting. The hole structure is intrinsically dispersive, and the size and placement of the holes can dramatically effect the optical performance. Indeed, the microstructure can be used as a modal “sieve” which confines the fundamental mode much more

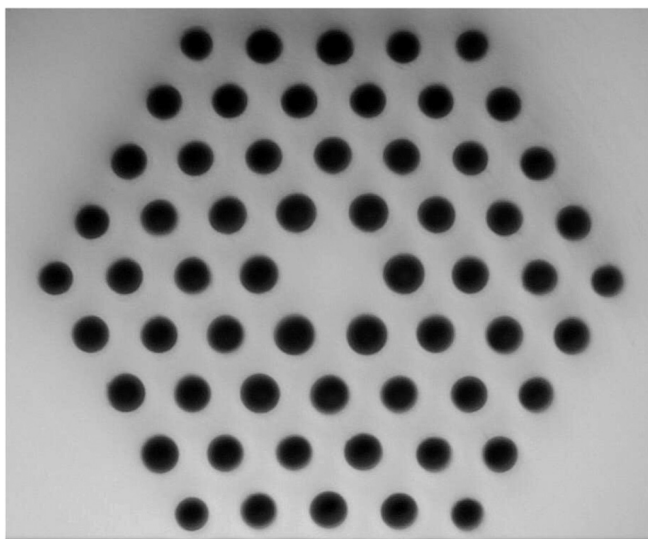


FIGURE 1 A microstructured fibre made from polymer. This is structure yields “endlessly single mode” behavior.

effectively than higher order modes [1]. This effect allows MOFs to remain single-moded over a very large frequency range [2].

Modifications of the microstructure have allowed an increasing number of specialty applications to be realized. For example by making the arrangement of holes, or the holes themselves have different profiles in the x and y directions it is possible to make highly birefringent or polarization maintaining fibres [3,4]. The dispersion properties of MOFs have also attracted attention particularly because of the possibilities they offer for dispersion compensation [5]. By changing the core size of the fibres, it is also possible to make them have either very low or very high optical non-linearity [6], and an appealing use of this property was the development of a fibre system for supercontinuum generation [7,8]. By making the bridges between the holes extremely thin, it is possible to make fibres which are essentially “air clad.” Such fibres can have numerical apertures greater than 0.9 [9].

A particularly significant feature of MOFs is that they offer the ability to guide light in air or other low index materials through the photonic bandgap effect [10]. Photonic bandgap effects are most simply understood in one-dimensional structures such as multi-layer stacks, which can be designed to reflect particular wavelengths. These wavelengths are described as lying within the “band gap” of the structure- they cannot be transmitted, and so are reflected. If we imagine this multi-layer stack to be rolled up into a cylinder, we obtain a “Bragg fibre,” in which the wavelengths with the bandgap are transmitted along the hollow core. Exactly this approach has been used to produce a “swiss roll” fibre, in which a two material multi-layer is rolled up to produce a hollow core fibre [11]. A simpler approach, which requires a single material, is to make a two dimensional microstructure. Microstructured fibres analogous to Bragg fibres can be produced using ring structures [12,13], or more commonly a two dimensional array of holes, is used to produce the bandgap. One of the most significant implications of photonic bandgap effects is that that they not only allow wavelengths to be guided that previously could not because of material absorption, but also allows guidance in materials of low refractive index, such as liquids or gases – something that is impossible using total internal reflection as the guidance mechanism.

MICROSTRUCTURED POLYMER OPTICAL FIBRES

The development in 2001 of microstructured *polymer* optical fibres [mPOF] [14] opened up a number of possibilities, particularly for the

polymer fibre community. Using this technique it is easy to make single-mode polymer fibre, which is problematic by conventional methods. Such fibres could have a large number of applications, particularly in sensing, where the ability to make materials sensitive to different stimuli is important. This is likely to be particularly important in combination with fibre gratings. Both conventional and long period gratings have been successfully written in mPOF [15,16].

Perhaps even more significant however is that polymers offer a variety of quite simple manufacturing techniques for making fibre preforms. Microstructured optical fibres are drawn from a “preform”, which is heated and drawn down into a fibre using a conventional draw tower. The preform is essentially a short fat version of the final fibre, with a larger version of the desired structure. In silica, the preform is normally constructed from a stack of capillaries and rods. This is a versatile and effective method, but time-consuming and fiddly. It also results in structures of restricted symmetries – normally a hexagonal packed structure.

By contrast, a whole range of polymer processing techniques can be brought to bear on making polymer preforms – extrusion, casting, molding, even drilling. These techniques can be used to obtain a range of structures that cannot be easily made in other materials. Figure 2 shows two such examples of unusual microstructures fabricated in polymer fibres.

The field of microstructured polymer optical fibres is therefore potentially rich indeed.

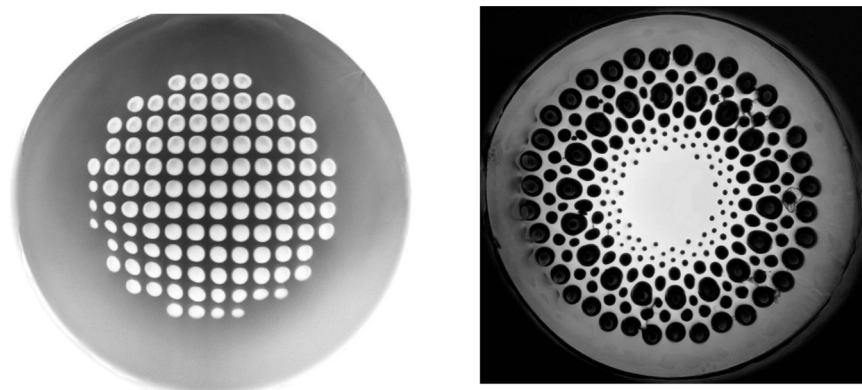


FIGURE 2 Two examples of mPOF showing some of the variety of structures that can be fabricated. The fibre on the left is a multi-core fibre, designed for imaging or interconnect applications [18], while the fibre on the right is a “graded index” fibre, designed for high bandwidth applications.

In this article we outline some of the challenges and opportunities that are afforded by microstructured polymer optical fibres. The aim is to give an overview of recent progress rather than to give an in-depth description of any particular aspect. More detailed descriptions will be presented in forthcoming publications.

LOSSES IN MICROSTRUCTURED FIBRES

Probably the main technical challenge facing mPOF is to reduce the loss of the fibres to levels comparable, or perhaps even better, than those of conventional polymer fibres.

Broadly, the loss mechanisms in microstructured fibres are:

- **Material losses.** Absorption and scattering from the bulk material from which the fibre is made. In conventional POF, the scattering losses are both due to inhomogeneities in the polymer itself, and the presence of dopants. As mPOF do not need to contain dopants, the latter effect is not necessarily present in mPOF. Impurities in the polymer however, or the presence of moisture will contribute to the material loss.
- **Surface scattering.** Scattering from interfaces may also be a problem with conventional step index POF, however, there are reasons for being even more concerned about surface scattering in mPOF: the surface area is very large, and the refractive index contrast substantial. A particular concern is that of particulate contamination, since the effect of these will not be reduced by the draw process. The experience in silica MOFs, suggests that surface scattering does indeed play an important role in determining the loss properties [17]. However surface roughness is greatly reduced by surface tension and the draw process.
- **Structural variations.** This includes both transverse and longitudinal variation of the microstructure. Microstructured fibres do not need to have a regular structure to guide through effective index guidance, and changes along the length of the fibre will not cause dramatic changes in loss if the change is adiabatic. Some changes however will have a serious effect on the loss – for example a hole becoming blocked.
- **Microbending losses.** These can be a serious contributor to losses in mPOF [18]. They can be significantly reduced by simply making the fibres physically thicker.
- **Confinement losses.** This is a mechanism unique to microstructured fibres. The “open” nature of the structure allows light to

tunnel through the bridges between the holes. This loss can be made arbitrarily small by changes to the microstructure, for example by adding further rings of holes, or decreasing the thickness of the bridges between the holes. It is important then, that the techniques used to model microstructured fibres, can also model leaky modes, although for massively multi-mode fibres, with mode-coupling, this is not a trivial problem.

Our recent investigation of loss in mPOF has concentrated on isolating the relative contributions of all these effects. We investigated the role of surface roughness by fabricating fibres whose structures [number of confining rings, hole spacings and radii], as well as their external radii were identical, but whose cores were different in size. The preforms and fibres were treated identically at each stage.

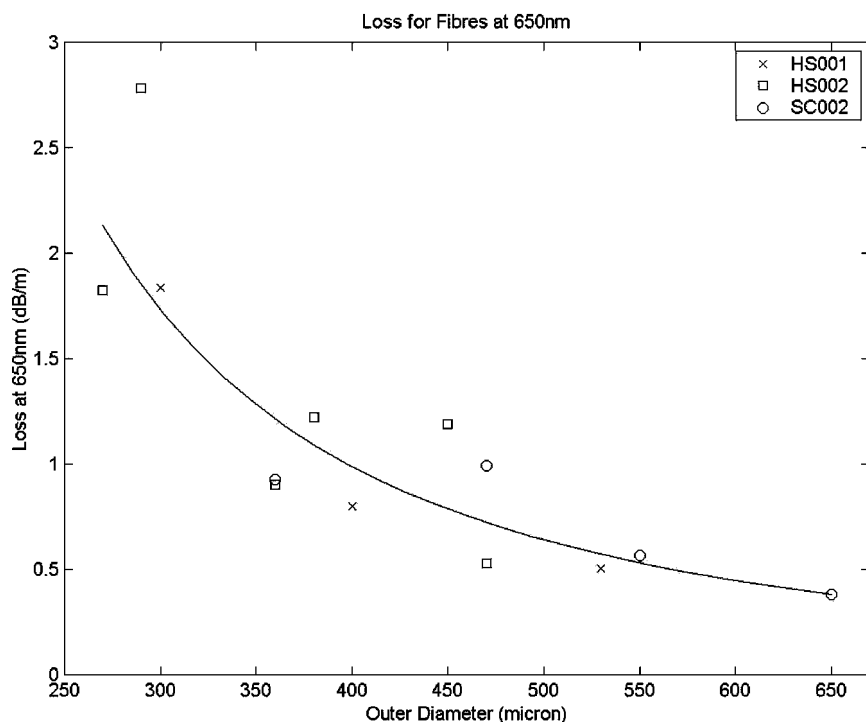


FIGURE 3 The effect of micro-bending. Three fibres with different structures were drawn to different outer diameters. The loss measurements on these fibres show that micro-bending is a significant contributor to the loss. All fibres were unjacketed. Standard step index POF has a diameter of 1 mm.

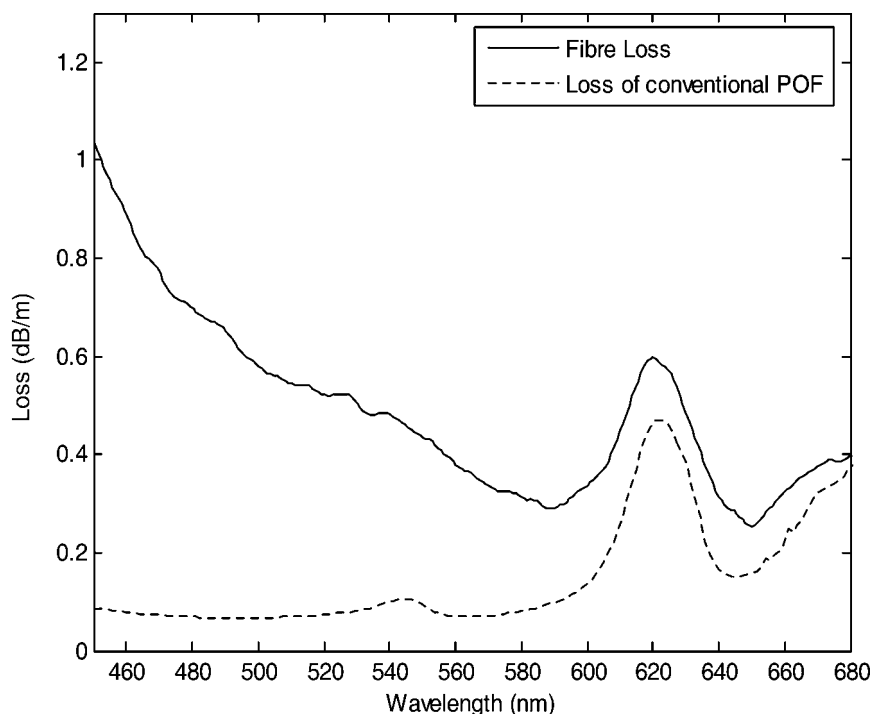


FIGURE 4 The lowest curve of the lowest loss mPOF yet produced. It is compared to a material loss dominated conventional POF.

If surface scattering were a dominant loss mechanism, the loss of the fibres with the smallest cores should have been higher than those with the larger core, reflecting the higher intensity at the surface. However, there was no significant difference between the fibres [19].

It is clear however that microbending remains an important contributor to loss. Increasing the external diameter of the fibre reduces loss for all structures we studied [see Fig. 3]. Our lowest loss fibre to date is a suspended core fibre [see Fig. 4], with a loss of 0.192 dB/m at 650 nm. This figure is beginning to be competitive with conventional POF, which has a loss of 0.15 dB/m at the same wavelength. Losses in this structure, which has a single ring of holes, are very dependent on fabrication conditions as small increases in the bridge thicknesses can increase the loss significantly, indicating that there is a remaining component of confinement loss present. Further studies aim at reducing loss further.

NEW DIRECTIONS FOR mPOF

Changing the Material Properties

A recently developed solution doping technique [20] allows many dopants to be introduced to the polymers after polymerization. The process exploits the large surface area of mPOF preforms. Using appropriate choice of solvents, doped solutions can be introduced through the holes of the microstructure. The solvent acts as a plasticiser which increases the diffusion of the dopant dramatically. When the solvent is removed, through heating, the dopant remains in the polymer matrix [Fig. 5].

This was recently used [21] to develop the first mPOF laser by doping with the laser dye Rhodamine 6G. This laser that was produced was unusual in having a much narrower line width than similar polymer fibre lasers. It also lased at a different wavelength (632 nm) was different to that of its gain maximum as an amplifier, which occurred at 574 nm. This effect was initially thought to be due to the optically thick fluorescence, in which lasing occurred at longer wavelengths due to reabsorption of the fluorescence. Subsequent analysis has shown however [22,23], that the lasing wavelength was in fact determined by a Raman shift of the 532.2 nm pump beam. Using a fibre of a different design allowed the Raman cross-section to be reduced, and

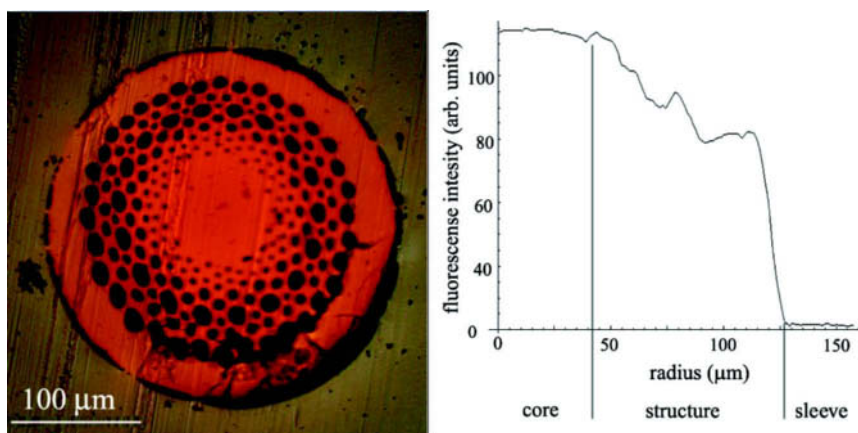


FIGURE 5 Solution doping can be used to dope preforms. In this case the preform was drawn to at an intermediate “cane” stage, and doped. It was sleeved with a plastic tube and drawn to fibre. The dopant here is the laser dye, Rhodamine 6G, and the fluorescence indicates that the dopant concentration is uniform. The holes in the cladding reduce the fluorescent intensity.

laser with a lasing wavelength of 568 nm was produced, with a line width of 5 nm, consistent with other reported lasers of the same type.

We have also developed a technique to incorporate electrodes into the fibre during drawing, allowing poling to be carried out, and are beginning to investigate poling of doped fibres [24].

A more unusual application relates to the inclusion of chiral materials. Circular polarization is associated with important physical phenomena, including Faraday rotation, in which linearly polarized light is rotated by the application of a magnetic field. Many biologically important molecules are optically active. This means that for a variety of important applications relating to sensing, circular birefringence offers the most appropriate optical route. For example optical electrical current sensors employing the Faraday effect may use interferometric approaches based on circularly polarized light. Circular birefringence offers a route to making optical fibres that are polarization maintaining. A suitable transparent chiral polymer has been developed [25], and work on producing a chiral mPOF is in progress. One of the motivations of this work has been to exploit the fact that circular birefringence is a robust material property. Linear material birefringence is often introduced accidentally through polymer processing and is similarly easily removed by annealing.

Photonic Bandgap Guidance

One of the most exciting features of microstructured fibres is their ability to guide in low index materials through the photonic band gap effect. The scientific enthusiasm generated by these possibilities is moderated only slightly by the difficulty in producing them. We however recently succeeded in making hollow core mPOF for the first time [26].

The fibres we fabricated were intermediate between Bragg fibres and 2D bandgap fibres. An example of the fibre structure is shown in Figure 6. The fibres were drawn down to a variety of diameters, ranging from 100–300 microns. The small size of the radial bridges allows them to be ignored, hence these fibres ideally resemble 1D Bragg fibres. In practice, the inconsistent thickness of the azimuthal polymer rings that lie between the rings of holes means the 2D nature of these fibres cannot be entirely ignored.

The transmission properties of the fibre were measured by launching light from a supercontinuum source into the core of a sample of fibre using a microscope objective. The output was coupled to an OSA by similar means. The transmission of two samples of different diameter and of 30 cm length is shown in Figure 7(a) and (b). Discrete

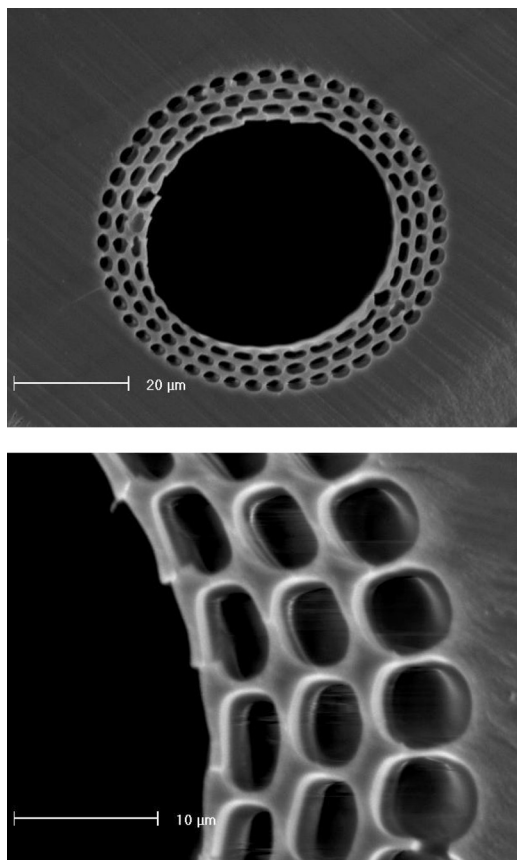


FIGURE 6 A scanning electron micrograph of a hollow core “Bragg” mPOF.

wavelength bands of high transmission, up to 200 nm wide, were observed as expected for bandgap guidance. The noise within the transmission bands arises from irregularities in the structure, such as the inconsistent thickness of the polymer rings. As fibres were made progressively thinner, the transmission bands were observed to shift to shorter wavelengths. In this way, transmission at any given wavelength can be achieved with the appropriate structure size. A comparison of the transmission with the transmission of the polymer is shown in Figure 7(c). A colour picture of the fibre guiding in air is shown in Figure 8.

These results are extremely significant for several reasons: they allow us to guide light below at loss levels below that of the material;

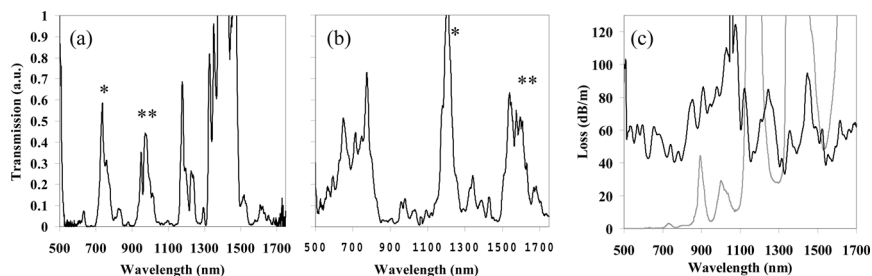


FIGURE 7 Transmission of a sample of approximately (a) 200 micron and (b) 300 micron outer diameter hollow core mPOF. The labelled transmission bands shift to shorter wavelengths as the fibre size is reduced from (b) to (a). (c) Loss of a third sample (black) and of PMMA (grey). Note that the loss is below the material loss for wavelengths >1100 nm.

they allow us to guide in low index materials, potentially the aqueous solutions for example, allowing a new variety of biosensing applications; and finally, they offer the possibility of making bandgap fibres *cheaply*. Whilst this is not a compelling scientific attraction, it may prove to be a very real technological virtue.

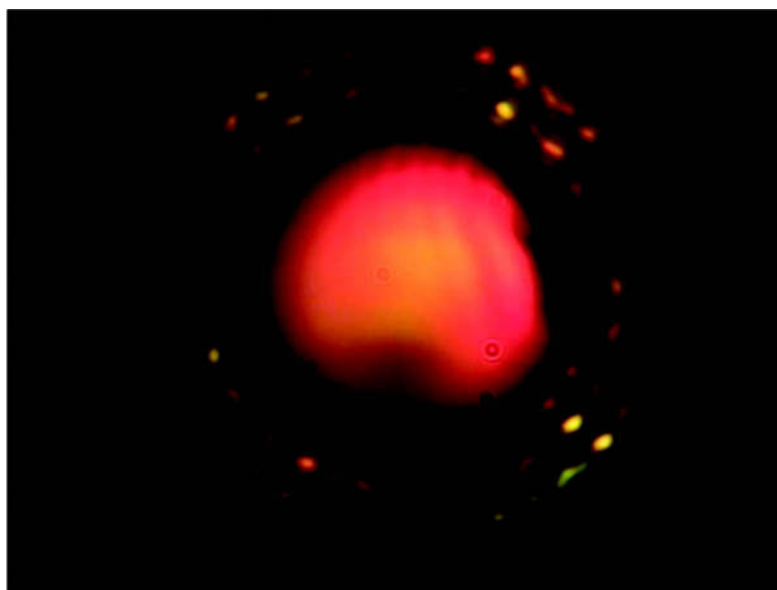


FIGURE 8 The hollow core mPOF guiding light in the core.

CONCLUSIONS

A rich range of possibilities has been opened up by the development of mPOF. Given the early stage of much of this research it is not yet clear which of the many possible applications will prove the most important. It is likely however that the most powerful use of this technology will combine more than one virtue of the technology to produce an effect that would not be easy, perhaps not even possible, by other means. Some of the qualities that could be combined in this way could be: the ability to introduce fluids into the holes (and still achieve guidance of light); to functionalise the surface of the polymer; to design the microstructure so as to optimize optical effects; to gather light very effectively; to have extremely long interaction lengths; to dope the polymer and to write gratings, and include electrodes. While there are still problems to be solved, with loss perhaps being the most urgent, there is plenty of scope for interesting research ahead.

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