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MICROSTRUCTURED POLYMER OPTICAL FIBRES
-the exploration of a new class of fibres-

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Abstract: *Progress on microstructured polymer optical fibres (MPOFs), a new class of polymer fibres that were developed last year, will be presented, including various single-mode MPOFs, highly birefringent MPOF, twin-core MPOF, nonlinear MPOF, graded-index MPOF and hollow core MPOF, the latter case being where light is guided in an air core.*

1. Introduction

A new class of polymer optical fibres was reported last year [1-5], in which the guiding of light is achieved by the introduction of a pattern of microscopic air holes that run down the entire length of the fibre. These microstructured polymer optical fibres (MPOFs) offer many new opportunities and can significantly enhance the functionality of POFs.

The idea to guide light using microstructure has been explored in silica fibres, in so called photonic crystal fibre (PCF), microstructured fibre (MOF) or holey fibre (HF) [6,7]. It has been shown that single-mode guidance in a relatively large core (20 µm diameter) [6] is possible, as well as guidance in an air core. MPOF allows many advantages over their glass counterpart. Firstly, fabrication is much easier due to the much more favourable balance between surface tension and viscosity at the draw temperature which reduces the chance of holes collapsing. Secondly, the microstructure is not restricted to close-packed arrangements of circular holes, as is the case for glass. Thirdly, more material modifications are possible, owing to the much lower processing temperatures and the intrinsic tailorability of polymers. This offers the potential of fabricating fibre with specific functionality not otherwise obtainable.

The combination of low-cost fibre fabrication and large-spot single-mode or multi-mode guidance provides potential advantages for MPOF in applications such as local-area networks (LANs). In addition, polymers with higher glass transition temperatures can be used for MPOF, offering advantages for high temperature applications e.g. in the automotive industry.

A large range of different fibres can be fabricated within the same fabrication framework. Simple changes in the microstructure can provide fibres with distinctly different functionalities. In this paper, we present an overview of recent MPOF work, including examples and results of single-mode MPOF, highly-birefringent MPOF, electro-optic MPOF, twin-core MPOF, Graded-Index MPOF, ring-structured MPOF, and hollow-core MPOF, in which light can be guided in an air core.

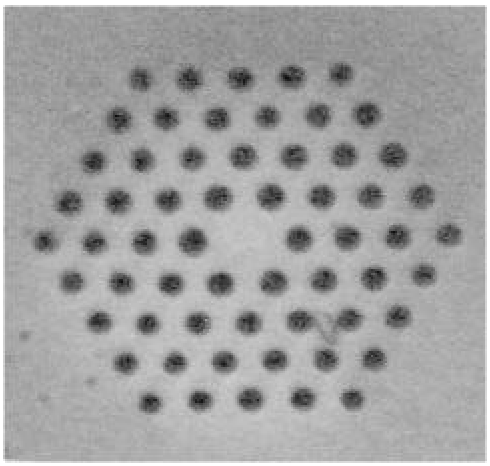

Fig. 1 Example of a fabricated single-mode microstructured polymer optical fibre (MPOF) with air holes spaced at 3.5 µm.

2. Fabriction and materials

A range of different materials and fabrication methods can be used to make MPOF preforms. In addition to the capillary stacking technique traditionally used for glass PCF, polymer preforms can be made using techniques such as extrusion, polymer casting, polymerization in a mould or injection moulding. With such techniques available, it becomes straightforward to obtain different cross-sections in the preform, with holes of arbitrary shapes and sizes in any desired arrangement (see Section 4). This is a major advantage over silica-glass based PCF, where the hole structure is mostly restricted to hexagonal or square close-packed structures due to the capillary stacking technique used.

Extruded Polymethylmethacrylate (PMMA) preforms with a Tg of 115 ^{o}C are used for the proof of concept exploratory experiments. This material has relatively poor optical quality; the scattering losses from impurities are at the level of a few dB/m. After proof of concept of a particular MPOF, the material is replaced with purified or fluorinated PMMA to obtain low-loss properties.

Microstructured polymer optical fibres are drawn at a rate of a few m/min at a constant high tension around 150 grams and a hot-zone temperature of 160°C. Structures such as shown in Fig. 1 are achieved along lengths of over 50 metres. The fibres generally have an external diameter of 200 µm and a microstructure with holes spaced at a few microns. Fibre diameter uniformity of ± 1 µm is achieved over tens of metres of fibre by a feedback control loop between the capstan speed and the fibre diameter monitor. This provides uniformity of the hole structure along the length of the fibre.

In drawing a microstructured optical fibre, there exists a balance between the surface tension and the viscosity of the material at the draw temperature [17]. Clearly, a high draw temperature, i.e. a lower viscosity, will give the upper hand to surface tension effects, leading to distortion of the hole structure, such as partial or complete collapse of the holes. This can be prevented by lowering the draw temperature, thus increasing the viscosity and maximising the fibre draw tension, though this is limited by fibre breakage.

At the drawing temperature, the surface tension of PMMA is ~0.032 N/m and the viscosity ~ 5×10^{6} Pa?s. This compares favourably with the equivalent values for silica glass commonly used to fabricate PCF, which has a surface tension of ~0.30 N/m and a viscosity of ~3.6×10^{6} Pa?s at the draw temperature. Clearly, in PMMA, the balance between surface tension and viscosity shows a ten times more favourable relationship as compared to glass, making MPOF drawing with PMMA an inherently more robust process than glass PCF drawing.

3. Single-mode MPOF

Fibres such as that in Fig. 1 were shown to be single moded at 633 nm, by demonstrating that the near and far field patterns are insensitive to the launching conditions and to bending of the fibre, and that an interference experiment with a standard single-mode fibre showed a clear interference pattern [1]. The chromatic dispersion of the fibre in Fig. 1 was measured to be 100 ps/nm.km at a wavelength of 855 nm, with a zero-dispersion wavelength of 1.35 µm [8]. Note that MPOF can be used for dispersion control, as high-dispersion microstructured fibres can be fabricated, as well as dispersion flattened fibres, where the dispersion is constant over a broad wavelength range for non-linear applications.

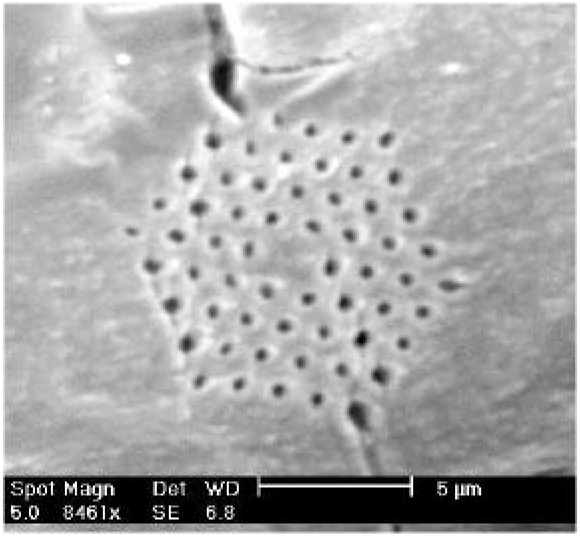

Fig. 2 Electron Microscope image of the single-mode microstructured polymer optical fibre with a core size of 2.1 µm [Image courtesy of the Electron microscope Unit Sydney University.]

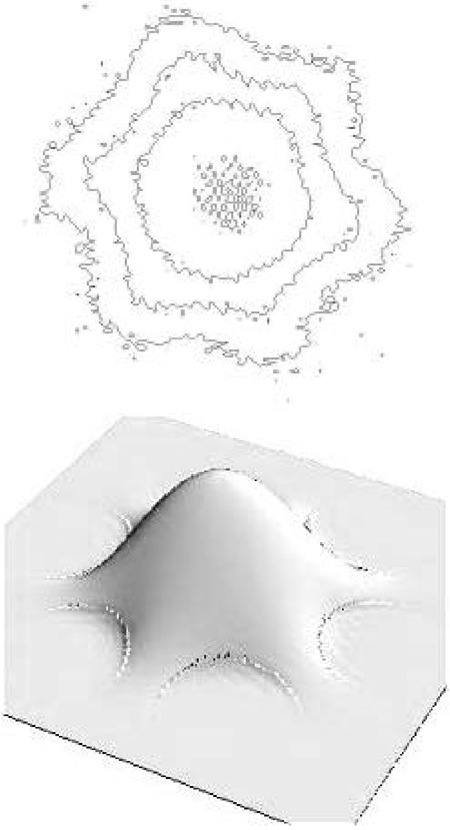

Fig. 3 Recorded contour plot of the guided mode in the core of the fibre in Fig. 2 (top) and a calculated fundamental mode profile (bottom).

By using a sleeving technique, similar to sleeving of conventional silica fibres, structures such as shown in Fig. 1 can be drawn down further, to achieve a smaller hole spacing. An electron microscope image of one such sleeved fibre is shown in Fig. 2. A hole spacing of 1.3 µm is achieved, along with a 0.48 µm hole diameter. The strong confinement achieved by the size-reduction of the hole structure increases effects such as waveguide dispersion, birefringence and non-linearity, each with their own potential applications. Figure 3 shows a contour plot of the measured near-field mode profile of the fibre shown in Fig. 2. The measurement is in good agreement with theory [16].

4. Graded-Index Multi-Mode MPOF

It has been shown that for small enough structures, the microstructure remains unresolved by the light, and the whole structure can be viewed as an effective refractive index profile, an average defined by the fraction of air in localised regions. This has been used to fabricate MPOFs with multiple depressed index rings (see Sec. 8 and [2]).

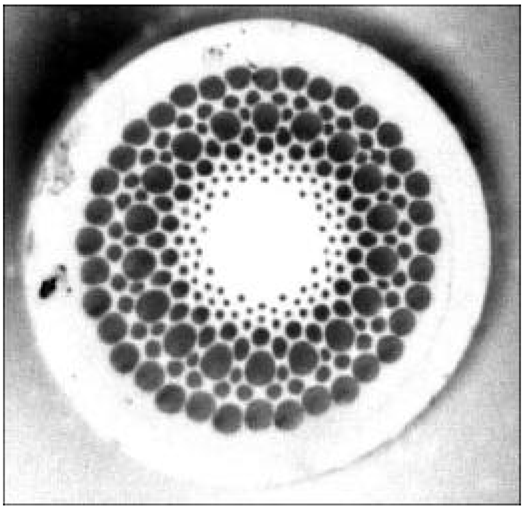

Fig. 4 Graded-Index Microstructured Polymer Fibre (GIMP fibre) demonstrating the ability to position differently sized holes in any desired arrangement, achieving –on average- a graded-index multi-mode fibre.

We have exploited the average-index effect by fabricating a large-core multi-mode MPOF with a graded hole structure as shown in Fig. 4. Light guiding in the 40 µm diameter core is achieved with a hole structure that is designed to compensate modal dispersion in a fashion similar to conventional graded-index POF. Hole diameters increase with distance from the core centre, so that the azimuthal average provides an approximation to the ideal near parabolic graded-index profile to compensate modal dispersion. Guidance has been obtained in these fibres, but more work is required to establish the potential transmission bandwidth. Experiments are being prepared with low-loss materials to enable this.

5. Highly birefringent MPOF

HiBi MPOF can be fabricated by introducing an asymmetry in the waveguide structure, e.g. by using arrangements of different hole sizes in order to break the symmetry, or by using elliptically shaped holes. This can lead to strongly birefringent fibre, with beat lengths below 1 mm as was demonstrated in silica PCF [9].

We have developed techniques to fabricate MPOFs such as shown in Fig. 5. This fibre was designed to exhibit high levels of form birefringence due to 1) the asymmetrical shape of the core, and 2) the elliptically shaped holes around the core. In conventional fibres, form birefringence leads to relatively small amounts of birefringence as compared to the much stronger stress-induced birefringence (e.g. bow-tie or panda fibres). However, in microstructured fibres, form birefringence can be very strong due to the large index difference between the air holes and the host material ($n_{PMMA} \sim 1.49$)

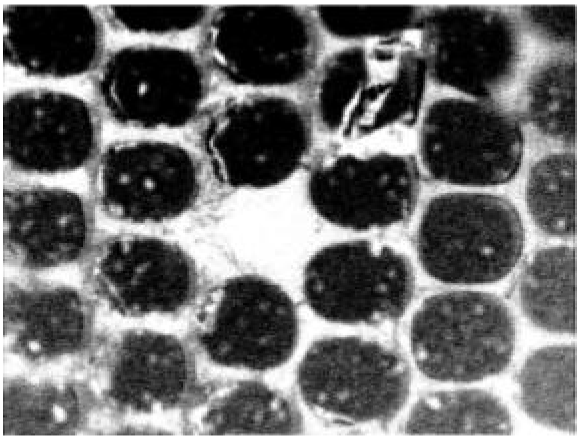

Fig. 5 Example of a single-mode highly birefringent MPOF. Polarisation beat lengths as small as 8 mm have been measured with such structures.

The birefringence of a fibre such as shown in Fig. 5 was measured using the technique reported in [9,18]. This showed a polarisation beat length of 8 mm at 800 nm [18]. By optimising the microstructure design, reducing the dimensions of the structure and by exploring the effects of non-circular holes, we expect to make highly birefringent MPOF with beat lengths below 1 mm ($\Delta n > 10^{-3}$) in the near future.

6. Electro-optic MPOF

Experiments are underway to fabricate electro-optically active MPOF with internal electrodes for optical sensing, switching and non-linear applications. Tungsten wires of 25 µm diameter have been drawn into long lengths of fibre, through holes directly next to the microstructure [19]. An optical microscope image of one such a fibre is shown in Fig. 6. The poling wires can be seen coming out of the end of the fibre, next to a single-mode guiding microstructure.

The fibre will be thermally poled, and the electro-optic coefficient will be measured interferometrically. Very tight confinement to a small core can be achieved with microstructured fibres, which enhances the effective non-linearity [10]. In addition, MPOF has the advantage that long lengths of fibre with internal electrodes can be drawn, thereby increasing the interaction length as compared to conventional poled silica fibres. Experiments are planned with highly non-linear polymer materials incorporated in the microstructure.

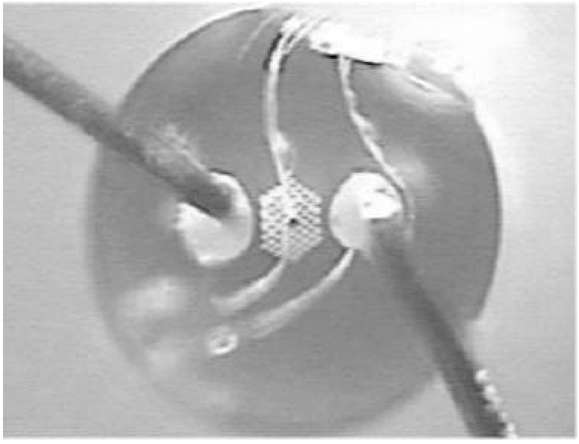

Fig. 6 A single-mode MPOF with metal electrodes intended for poling experiments.

7. Twin-core MPOF

A twin-core MPOF as shown in Fig. 7 has been fabricated by omission of two rather than one hole to create the cores. The periodicity of the hole structure is 4.8 μm, leading to a spacing of 9.6 μm between the centres of the two cores.

The fabrication of twin–core MOF is much less involved than the fabrication of conventional twin-core silica fibre, which requires chemical vapour deposition to make two preforms, which are subsequently sliced in half (slightly off centre), polished and fused to form a single preform with two cores. Fabrication of silica fibre with more than two cores is even more complicated. In contrast, multiple-core MPOF is fabricated in a single stage, using exactly the same technique as used for a single-core MPOF.

Multi-core fibres are attractive for applications in optical fibre sensing. One example is in the use of a two-core MPOF for strain measurement, specifically for measuring curvature in engineering structures by interrogating the two cores interferometrically [11]. As the two cores are embedded in the same cladding structure, common mode rejection is very effective at preventing unwanted sensitivity to external disturbances. Conveniently, the exit face of a twin-core fibre, with two single-mode localised spots, acts as an ideal fringe projector.

The coupling length of the twin core MPOF shown in Fig. 7 was measured by launching white light into one core and collecting light from the other end with a spectrum analyser. From the measured spectrum, a coupling length of 6.8 mm at 650 nm could be inferred.

Calculations were performed using the ABC FDM method [16], taking into account the actual structure of the fibre, including slight structural asymmetries. One of the holes next to the core was found to be significantly larger than the other holes, and the effect was a remarkable reduction in the coupling length. Good agreement between experiment and theory was found [20].

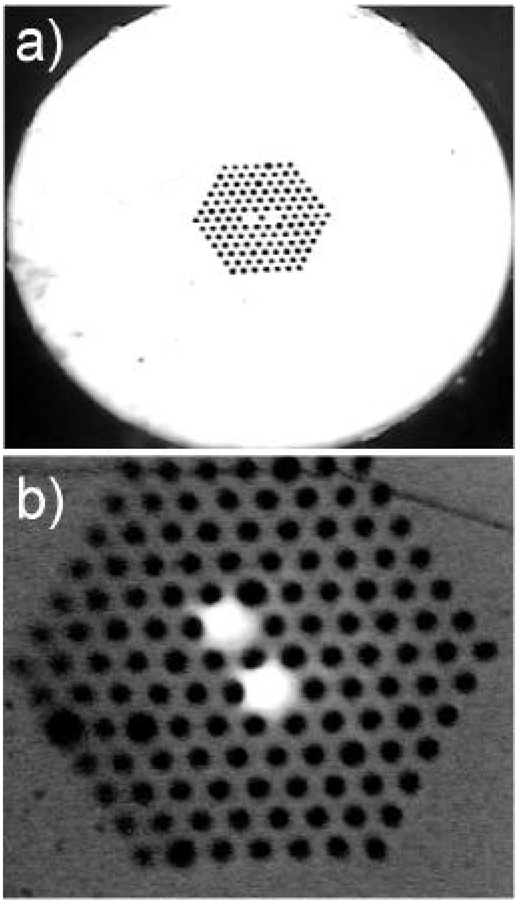

Fig. 7 Twin core MPOF with two cores separated by 9.6 μm. The coupling length was measured to be 6.8 mm at 650 nm.

8. Ring structured MPOF

Single-mode microstructured polymer fibres in which the air holes are positioned on concentric rings have been fabricated [2]. These structures can be used to reduce splice losses of microstructured fibres [12] and to achieve strongly wavelength dependent effects such as Bragg reflection. An in-depth theoretical analysis has shown that rings of sufficiently closely spaced air holes act as rings of depressed refractive index [2]. Based on the 'index-averaging' effect, ring structured MPOF can be used to fabricate multi-layer Bragg fibres, in which the guidance is achieved though Bragg reflection off the rings of air holes. This makes guidance in a central air core possible, and even pure single-mode single-polarisation guiding is possible [13,14]. Bragg fibres were fabricated, but despite the observation of strongly coloured transmission in the cladding, indicating Bragg effects, the fibres did not show guided modes in the air core. This is attributed to non-uniformities in the fibre structure, both in the transverse and longitudinal direction, and to the number of rings used being too low to achieve low loss.

9. Photonic band gap structures

In a photonic band gap fibre, light is guided due to the photonic band gap (PBG) effect, similar to the electronic band gap for electrons in semiconductors. The microstructure, with a periodicity of the order of the optical wavelength, prohibits propagation of certain wavelengths through the cladding. This effect can be used to confine light to a fibre core. Since the guidance does not rely on total internal reflection, the core can either be a solid core, or, more importantly, an air core [6,15]. Air-core guidance in a PBG MPOF can reduce the effects of material absorption, and thus provide a possible new route to achieve further reduction of the losses of POF.

Air-cored PBG polymer fibre as shown in Fig. 8 has been fabricated. First evidence of photonic band gap guiding through short lengths of fibre with a structure as shown in Fig. 8 b) has been observed [15]; a brightly coloured orange mode was transmitted through the air core when white light is launched into the fibre, a signature of PBG guiding. On-going work is focusing on the fabrication of PBG MPOF with a larger air fraction and a smaller hole spacing, in order to achieve a larger bandwidth of the guided light.

10. Conclusions

Microstructured polymer optical fibres (MPOF) are an exciting new development in POF research, offering opportunities to develop fibres with new functionalities for specific applications. We presented an overview of our recently fabricated MPOFs, including single-mode MPOF, highly birefringent MPOF, graded-index MPOF and air-core photonic band gap MPOF. These new fibres clearly have a bright future ahead of them, and we have only just begun to realise the true potential of these fibres.

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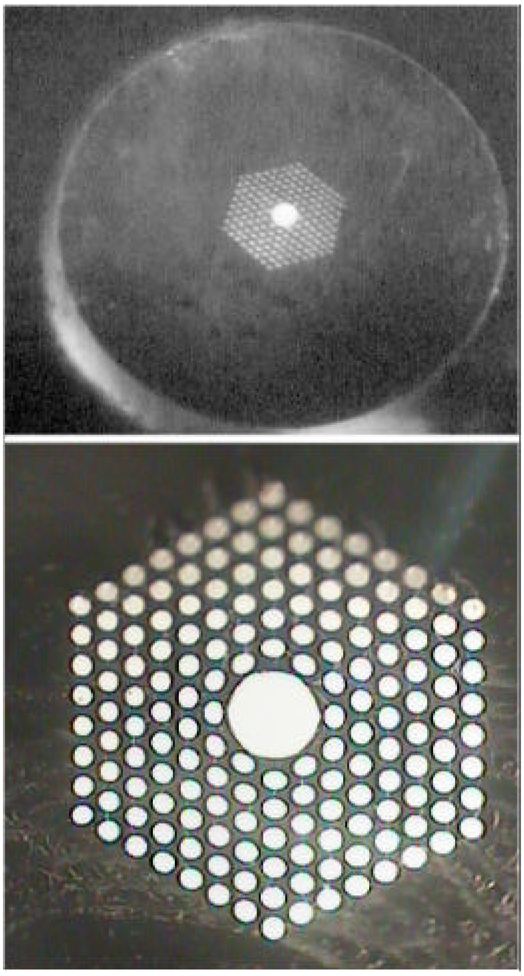

Fig. 8 Examples of fabricated photonic band gap MPOF. a) shows an air-core fibre of 220 μm external diameter, and b) shows a close-up of the micro structure with a 5 μm hole spacing.

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