Casting preforms for microstructured polymer optical fibre fabrication

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Abstract: A monolithic structured polymer preform was formed by in-situ chemical polymerization of high-purity MMA monomer in a home-made mould. The conditions for fabrication of the preforms were optimized and the preform was drawn to microstructured polymer optical fibre. The optical properties of the resultant elliptical-core fibre were measured. This technique provides advantages over alternative preform fabrication methods such as drilling and capillary stacking, which are less suitable for mass production.

OCIS codes: (220.0220) Fiber design and fabrication; (160.5470) Polymers; (230.4000) Microstructure fabrication.

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1. Introduction

Microstructured optical fibres (MOFs), also known as "photonic crystal" or "holey" fibres, produce their light guidance effects through a pattern of tiny holes which run along the entire length of the fibre. Depending on the hole pattern, the fibres can have unusual properties. For example they can be single-moded over a very large frequency range [1], be single-moded with a large mode area [2], be highly birefingent [3-5], or have tailorisable dispersion properties [6,7]. 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 [8], and they can even be made to transmit in air through the photonic bandgap effect [9,10].

Most work to date has concentrated on silica fibres, where the preform is produced by capillary stacking [1] or casting using sol-gel techniques [11]. More recently microstructured fibres have been made in polymer [12], where the most commonly used preform fabrication technique is drilling with a CNC mill [13]. Capillary stacking has also been used [14-16] and

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billet extrusion is being explored for novel designs [17] but none of these are particularly suitable for mass production.

The mass production of preforms for microstructured fibres is an issue for the uptake of the technology, particularly for polymer fibres, where the commercial opportunities require low cost production. In this paper, we explore the use of casting for making preforms for microstructured polymer optical fibres (mPOF). Casting is an option that has been used to produce both glass and polymer preforms. In case of glass, casting involves sol-gels, in which an intermediate preform is made by pouring the sol into a mould as described. The sol is transformed into a gel to obtain a gel body defining the intermediate preform which can be removed from the mould [11, 18, 19]. Casting methods provide advantages over bundling or stacking methods since the hole pattern, size and spacing can be altered independently and it does not create interstitial holes within the lattice.

For polymer preform casting, the necessary chemical precursors (i.e. monomer, initiator and chain-transfer agent) are introduced into a mould that mirrors the required preform hole structure [20-23]. After the polymer has ‘set’ the solid structure is removed. In most cases, the mixture in the mould requires degassing to avoid bubble formation during polymerisation and often the reaction takes place in vacuum. The casting of preforms for mPOF has been demonstrated with PMMA very early on in the mPOF development, in which a fibre was drawn from a preform of 50mm diameter and 250mm length with a hexagonal pattern of four rings of holes [24], and a large-effective area mPOF was fabricated through casting of a structured preform with 30 holes in a two-layer hexagonal arrangement [25], the fabrication details of which appeared in a recent patent publication [26].

Many variations of casting exist, such as casting around a structure that should be remained in the preform (eliminating the need to remove the hole forming elements), or casting around a stack of capillaries to fill in the interstitial holes, or casting into the gap between a structured cane and a sleeve to create a seamless drawable join between the two. Casting offers key advantages over both conventional capillaries stack-draw and drill-machining methods: by varying structure of the mould, it is easy to make various preforms of specialized fibres with holes of arbitrary shapes and sizes in any desired arrangement on a large scale. Casting in a sealed vessel also limits the possibility of chemical and physical contamination that could cause optical inhomogeneity, and thus improving the performance of scattering losses in the fibre.

Here we report on the fabrication of a large 7 cm diameter cast PMMA preform with 88 holes in a hexagonal arrangement and an overall length of 40 cm. A structure is incorporated to produce a highly birefringent (HiBi) fibre with an elliptical core by leaving out three holes in a line to form the core. Highly birefringent microstructured fibres have been investigated in detail, with the world-record birefringence achieved in a MOF in 2000 [3] for a fibre with a beat length of 0.4 mm, and a birefringence of 3.7×10^{-3} at 1540 nm. There have been reported a wide range of microstructured fibres made and studied theoretically for high birefringence applications. These fibres typically have an arrangement of holes that differ in the x and y directions, or have non-circular holes [4, 5]. In general the form birefringence of microstructured fibres is larger than the stress birefringence of conventional HiBi fibres. The birefringence is strongly dependent on wavelength, but very weakly dependent on temperature. One novel feature of microstructured fibres has been exploited to make the birefringence tunable. By selectively filling some of the holes with polymer a high degree of birefringence can be introduced, where the change of the refractive index of the polymer can be tuned by controlling the temperature [27].

2. Preform fabrication

A single mould may be costly to design and produce. However for large production runs it turns out to be very economical as many thousands of moulded items can be produced from a

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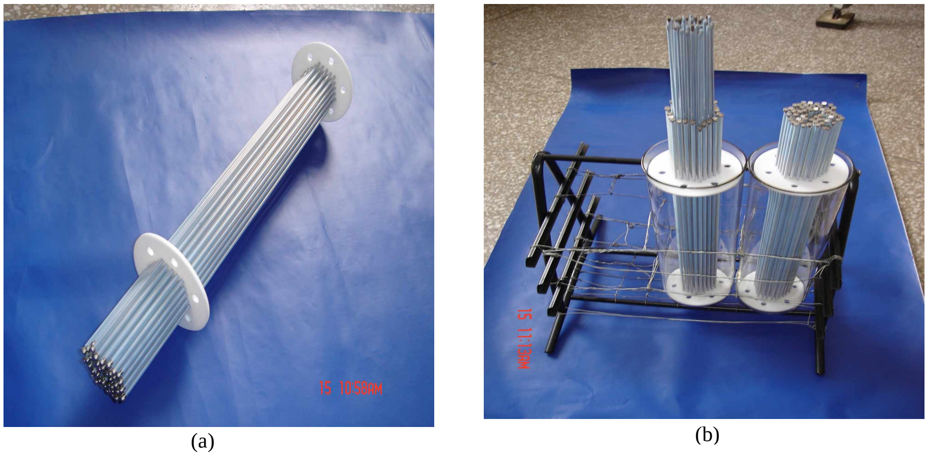
single mould. The moulds used in the process are generally made from alloy stainless steel and are constructed from a number of separate parts to allow the mould to be opened and to allow the moulded items to be easily removed. All moulding cavity surfaces must be smooth and highly polished to ensure a good quality of finish to the moulded items. A set of structure generating elements (e.g. steel wires or rods) in the mould define the final structure of preform. These are often releasably attached to allow individual removal. This may be facilitated by having conically shaped elements or by coating the elements with some low adhesion substance like polytetrafluoroethylene. Alternatively the preform or the elements may be heated (by running current through them) or cooled to exploit thermal expansion differences to loosen them.

The mould design required us to define a particular target fibre. We selected an elliptical core five ring hexagonal structure, with a hole-diameter (d) of 2.5 μm and a hole-spacing (Λ) of 6.25 μm. This "three defect" elliptical core design has been studied previously [28]. We aimed to make the fibre using a preform with a diameter of 70 mm, hole diameter of 2 mm, and hole-spacing of 5 mm. A mould to make this preform was made using a glass tube, two Teflon plates and 88 metal rods. The rods defined the holes in the preform, and Teflon plates were used to hold the rods in place. The height of the mould was 50 cm and is shown in Fig. 1.

In order to obtain a high-quality preform, the pre-polymer was prepared by using high-purity methyl methacrylate (MMA) as monomer, with Benzoyl peroxide (BPO) as polymerization initiator, and dodecanethiol (DDM) as chain transfer reagent. The monomer was distilled in vacuum distillation. The polymerization initiator, BPO was purified by re-crystallization, and DDM was purified by rectification. MMA was polymerized into pre-polymer by heating a mixture of MMA-BPO-DDM at 85°C for 3 hours. The pre-polymer was cast in the mould. The processing procedure took about 72 hours and included three key stages: low temperature polymerization, homogeneous polymerization and post-polymerization. Figure 2 shows the optimal control temperature at the different polymeric stages in the whole polymerization process. In order to reduce the formation of bubble defects, a nitrogen feed was used during the post- polymerization stage to expel bubbles produced by the residual monomer and the volume shrinkage. After gradually cooled to room temperature, the glass tube acted as the mould wrap can be easily removed. It should be pointed out that each of stainless steel rod was coated by the polytetrafluoroethylene tube, this makes them can be easily pulled out from the mould. Figure 3 shows a photograph of a preform rod fabricated in this technology. It can be seen that the designed holes were ideally retained in the preform rod. The longest preform rod was 40 cm and with the diameter of 7 cm, it is large enough to produce more than a hundred kilometers of fibre.



(a) (b)

Fig. 1. Moulds used to make the preforms: (a) a mould core and (b) two assembled moulds.

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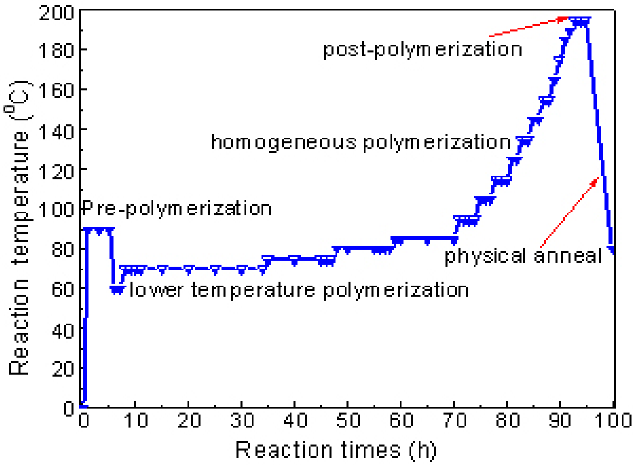

Fig. 2. The temperature cycle used during the polymerization process.

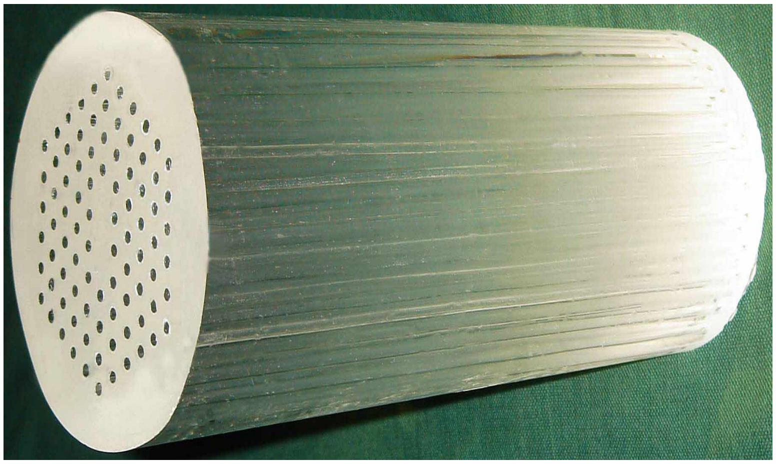

Fig. 3. A casted 88-holes PMMA microstructured preform with the hole diameter of 2mm, overall length of 40 cm and preform diameter of 7 cm.

3. Fibre fabrication and characterization

The large size of the preform made it appropriate to use a three stage draw process to produce the fibres, similar to the two stage process that has been used previously [13]. The first stage involved stretching the preform into the secondary preform or 'cane' in a home-made primary draw oven at temperature of 185 °C. The diameter of the preform rod was reduced to 25 mm, with a length of about 3m. This cane was cut in half and redrawn to 15 mm diameter cane with a length of 10m. The hole-diameter of these third preform rods was 0.25 mm and hole-spacing was 0.625 mm. The structure of the preform was maintained in this process. The final cane was sleeved and drawn to fibre using a commercial draw-tower.

Figure 4 shows a microscope image of cross section (a) of the resultant elliptical core mPOF and the scanning electron microscope (SEM) of core region (b), the hole size of the core region becomes bigger slightly. The unsleeved fibre diameter is 150 μm; hole-diameter was 3.5 μm, holes-spacing was 9.1 μm and d/Λ was 0.39 (compared to 0.4 in the initial preform, indicating only slight hole shrinkage during the draw process). Overall the structure

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of the preform was well maintained during the fibre draw. The dark circle ring in Fig. 4(a) corresponds to the interface between the fibre cladding and the sleeve. Near field and far field images of the fibre guiding are shown in Fig. 5. Cut-back measurements gave a loss at 980 nm of about 24 dB/m. The absorption of pure PMMA at this wavelength is about 15 dB/m. We have not yet investigated the relative contributions of different loss mechanisms but clearly there is considerable scope for our fabrication process to be improved, by for example using cleaner conditions to reduce contaminations.

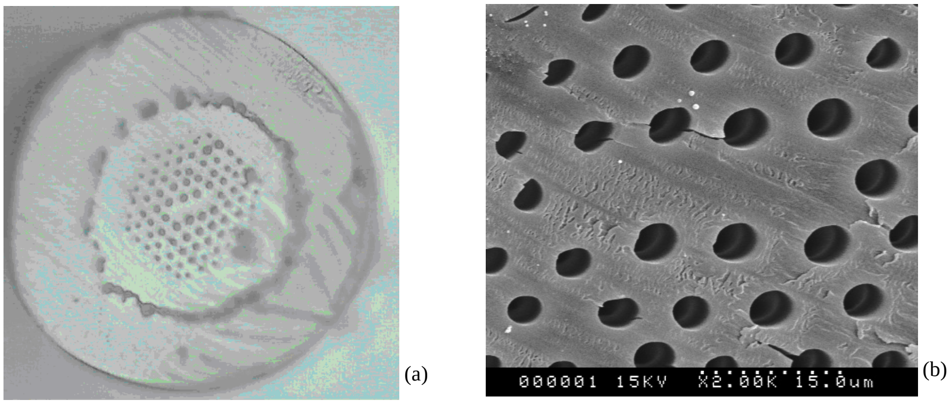

Fig. 4. Electron microscope images of the elliptical mPOF cross-section (a) and SEM of the core region (b).

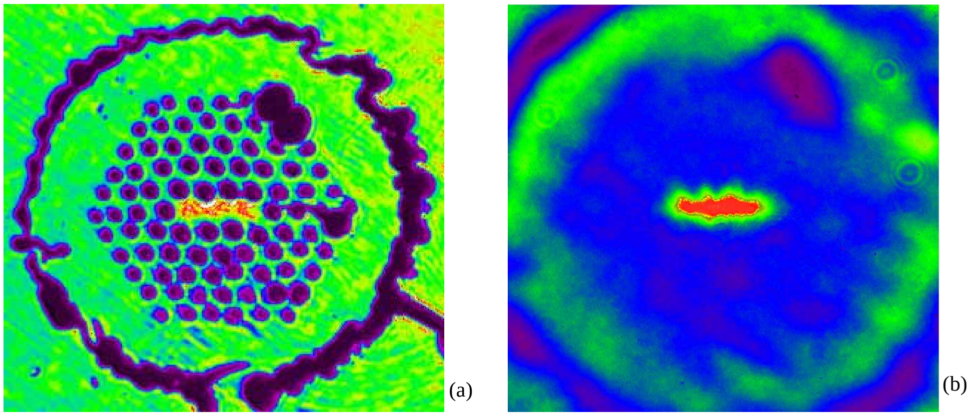

Fig. 5. The near-field pattern (a) and far-field pattern (b) of a resultant elliptical core mPOF.

4. Conclusion

While preliminary, these results have significant implications for potential mass-production of microstructured polymer optical fibres. MPOF have a large range of potential applications from large-core graded-index fibres for short distance, high data-rate transmission [29], to band gap fibres for sensing and medical applications [10]. Their commercial uptake will require the use of a cheap and effective alternative to drilling as preform production technique. The results of this work show that casting has the potential to play this role. The preforms described in this work are simple and cheap to make, and are large enough to produce well over 100 km of fibre. It is also straightforward to produce many different fibre structures, including for example, fibres with non-circular holes.

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