Microstructured Polymer Optical Fibres: Progress and Promise

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ABSTRACT

Microstructured optical fibres (MOFs) have aroused great interest in recent years because of their unusual optical properties. These include their ability to be effectively single-moded over a very large range of wavelengths, tailorisable dispersion, high or low non-linearity(depending on the hole design) and large core single-mode fibres. We have recently fabricated the first Microstructured Polymer Optical Fibres (MPOFs), which further extend the range of possibilities in MOFs.

The properties of polymers can be tailored to specific applications (eg. made highly non-linear or having gain) in a way that is not possible in glass. Further, the large range of fabrication methods available in polymers, including casting and extrusion, mean that structures can be obtained that are very difficult to make by capillary stacking- the method used in glass MOFs. Here we present the latest results from our group using MPOFs, including single-mode fibre and Bragg fibres.

Keywords: Microstructured optical fibre, MPOF, polymer optical fibres, Bragg fibres

1. INTRODUCTION

Microstructured optical fibres have aroused considerable interest since their invention. Among the interesting novel features associated with microstructured fibres are their "endlessly single-mode" [1] properties, easy tailorability for dispersion and polarization control, the possibility of large core single moded fibres [2], and even the ability to make band-gap fibres in which the light is guided in air [3]. These features mean that they are the subject of a growing research and development effort. In this paper we describe the first microstructured polymer optical fibre (MPOF) [4], and discuss the additional features that MPOF may bring to the area of both polymer fibre and microstructured fibre research.

MPOF has advantages over the existing polymer optical fibre (POF) technology in that it potentially addresses the features limiting the uptake of POFs. Traditional large-core multi-mode step-index POF suffers from very large modal dispersion. The fabrication of single-mode POF, ideal for telecommunication purposes, has proved to be challenging, and the associated small mode area limits the applications. The technology used to manufacture the current state-of-the-art POF, the large mode-area graded-index multi-mode POF (GI POF), relies on a complex polymerization process to obtain a particular graded refractive-index profile across the diameter of the fibre. This process involves free radical polymerization and the selective addition of a low molecular weight dopant to the polymer, which requires the use of a polymer with a relatively high glass transition temperature to prevent diffusion of the dopant at normal operating temperatures. These restrictions greatly reduce the choice of monomers.

A further reduction of the number of useful polymers is related to the absorption losses in the material, which has led to the use of fluorinated polymers. However, even in the case of these fully fluorinated materials, the use of conventional

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POF is limited to a few hundred metres. Scattering losses in polymers are associated with small fluctuations in refractive index caused both by the molecular weight distribution of the polymer and local variations in dopant concentrations.

By contrast, MPOFs require only a single material, so all problems associated with doping the material, to obtain the desired refractive index profile are bypassed. An appropriate choice of hole structure can be used to obtain the desired refractive index profile, including step index, graded index, or more complex structures. The use of a single material also avoids incompatibilities in the rheology of drawing. Fluctuations in dopant concentrations are a major source of loss in POFs, and one that will not apply to MPOFs, although other loss mechanisms will apply, such as confinement loss and structural variation.

MPOFs open up a large range of options in terms of materials, not just in terms of low loss materials, but also specialty polymers which have been functionalised for particular applications, such as dyes, chiral materials, and materials having a high optical non-linearity. These are likely to be of importance in device applications, and offer a key advantage over the glass microstructured fibres in specialized applications. In addition, MPOFs can be used to produce structures that are not easily fabricated in glass, both because the glass process relies on capillary stacking, and because alignment of the polymer chains during draw-down preserves hole structures better than is possible in glass. In particular, it is easier to produce non-circular holes.

2. SINGLE-MODE MPOF

MPOFs were fabricated using commercially available PMMA without further purification. Although this material is optically poor, it has allowed us to rapidly prototype many designs and establish fabrication methodologies.

Cut-back measurements performed on rods of PMMA with highly polished ends, showed a loss of some 4 dB/m, mostly due to scattering. This figure varied greatly from batch to batch. Loss measurements performed on an unstructured fibre showed a similar loss associated with scattering from the surface, due to surface roughness and cleanliness. This relatively high interface loss in the blank fibre was due to handling damage, and contamination, which will not be applicable to internal holes. The loss values associated with both the materials and structure are currently very high, because we have not yet refined our process beyond a “proof of concept” or prototyping level. Loss studies of MPOFs are under way, both experimentally and theoretically.

The performs were fabricated using a proprietary process, and drawn at temperatures of between 180° C and 220° C. The draw rate was 10m/min. Some hole shrinkage was observed during the drawing process. Compared to the dimensions of the preform, the fibre has a hole diameter to hole spacing ratio, $d/\Lambda = 0.46$, whereas in the preform $d/\Lambda = 0.67$. The average hole diameter $d = 1.3$ μm and an average hole spacing $\Lambda = 2.8$ μm, giving a core size of 4.3 μm. The numerical aperture of the fibre is 0.11, and it has a minimum bend radius of 2mm. The fibre is shown in Figure 1. Some holes in the structure have been filled with the resin used in preparing the sample for SEM.

Three experimental tests were performed to establish that the fibre was single-moded at 633nm. In the first experiment the fibre was butt-coupled to multi-mode fibre and was observed to give a stable pattern regardless of launch conditions. In a second experiment, a HeNe beam was launched directly into the fibre, and the expected near and far field images were observed. Finally, a spatial interference experiment was performed, in which the output of the MPOF and single-mode fibre was observed to give a stable interference pattern, with visibility of close to one- again independent of launch conditions. Figure 2 shows the results of optical tests on the single mode fibre.

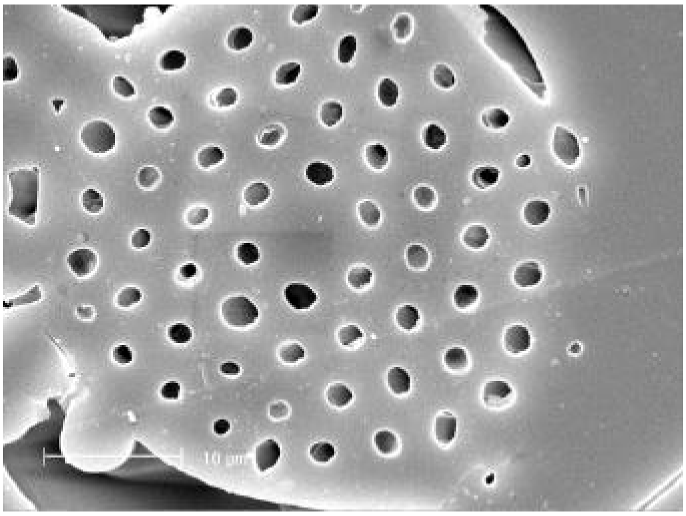

Figure.1. An electron micrograph of the microstructured polymer optical fibre (MPOF).

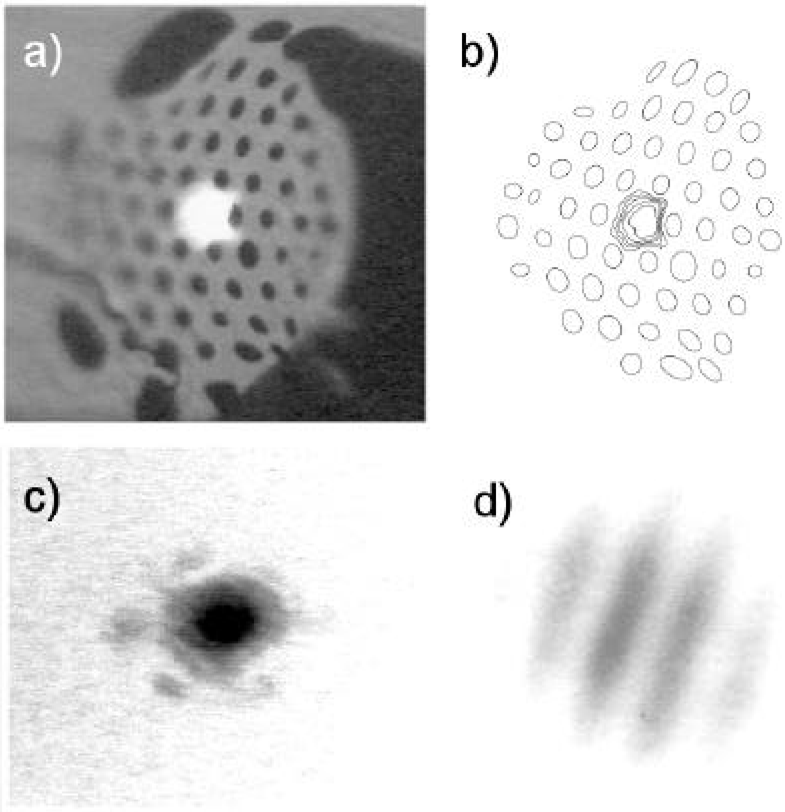

Figure 2. Optical testing of the single-mode guiding of the microstructured polymer optical fibre (MPOF). a) the mode pattern in the near field, b) a contour plot of the near field pattern, c) the far field mode pattern d) the interference pattern between a standard single-mode fibre and the MPOF.

3. MULTIPOLE MODELING OF THE MODE STRUCTURE

We modeled the MPOF using a recently developed multipole method [5,6], which has advantages in terms of speed and accuracy compared to other techniques. Crucially it also has the ability to calculate confinement losses. Confinement losses are a function of the number of rings of holes. The results show the structure to have three bound modes, two of which are doubly degenerate, together with a non-degenerate mode located in close proximity to the second degenerate mode. However the confinement losses of these modes are very different. In a four-ring case the fundamental mode exhibits a loss of $3x10^{-6}$ dB/m, which is much smaller than the material losses, and is therefore essentially negligible. In contrast, the higher-order modes have a loss around 200 dB/m. The theoretical results are therefore entirely consistent with the experimentally observed single-modedness, and suggest that a useful definition of “single-moded” in microstructured fibres could be fibres for which only one confined mode has confinement losses substantially less than other losses, for example material losses, scattering and losses due to manufacturing variations in the structure.

The axial component of the Poynting vector for the first two degenerate modes of a two-ring structure is shown in Figure 3. The holes of the fibre are located at the positions where indents are observed in the mode profile of the second mode.

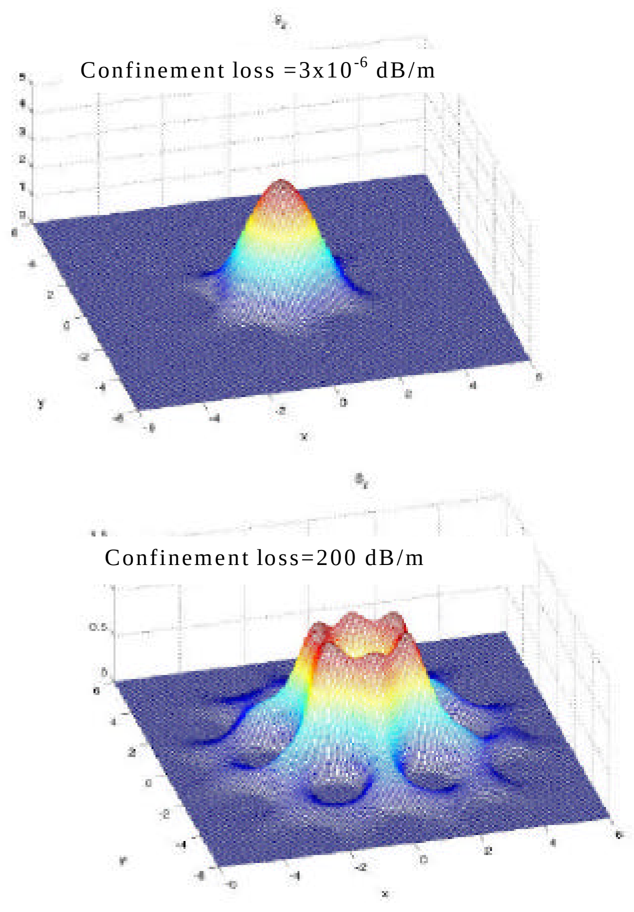

Figure 3. The axial component of the Poynting vector for the first two degenerate modes of a two-ring MPOF.

3. RING STRUCTURES IN MPOFS

One of the key advantages of MPOFs is that the fabrication methods allow a very large variety of structures to be made. Many of these structures are problematic, if not impossible, to make by capillary stacking. We have therefore sought to exploit this advantage by investigating novel structures. One such structure, not previously fabricated in MOFs, is the concentric ring structure, which is of particular interest because of its ability to approximate Bragg fibres [7]. Such structures have been theoretically considered in relation to bending losses and large-core single-mode guidance [8]. A key motivation for the Bragg fibre approach is the hope that an air core holey Bragg fibre will prove more robust to manufacturing variations that conventional air core MOFs, which rely on the perfection of the structure, rather than an averaging effect.

Bragg fibres have been actively studied as they present interesting modal and dispersion properties and features such as modal filtering and guidance in an air core. A similar structure to Bragg fibres to which ring structures could be applied is the dielectric coaxial waveguide [9] which mimic the properties of conventional coaxial cable for optical frequencies. The development of Bragg fibres has been problematic due to a number of fabrication difficulties; adequate confinement in Bragg fibres requires either a very large number of cylindrical layers, or a small number of large index contrast layers. Microstructured ring structure fibres can potentially provide a way to achieve the latter.

Preforms for the holey Bragg fibres were prepared using the same process as for the hexagonally structured single mode fibre described in the previous section. Figure 4 shows a number of ring structured capillaries that have been stacked and drawn down, a process that allows us to examine several cores simultaneously. Each of the cores shown in Figure 4 was drawn from the same perform. The picture has been included to illustrate the variety of hole sizes that can be obtained from a single draw, by varying the drawing conditions.

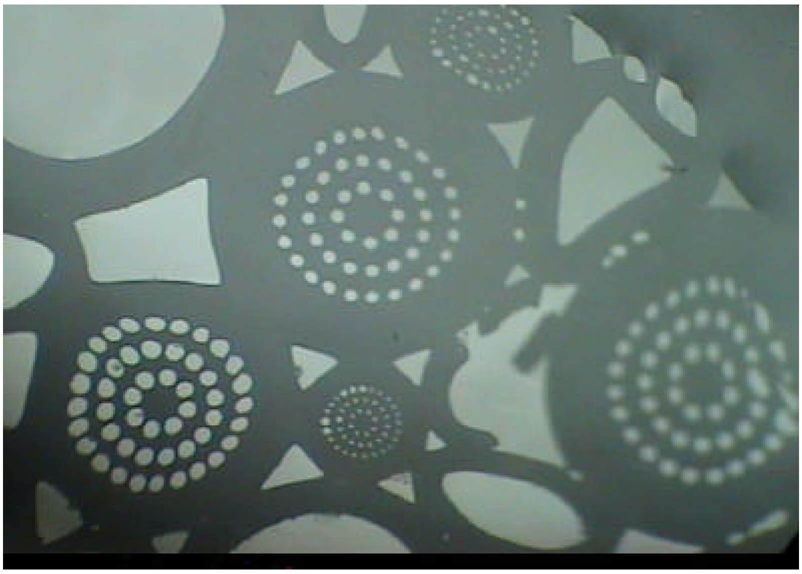

Figure 4. Optical micrograph of the cross section of the preform neck-down region. The image width corresponds to approximately 1.5 mm. Several ring structured sections can be seen with different sized holes. The structure on which the optical experiments were conducted and which was modelled is that in the lower left corner with the larger holes.

Considering only the core that resulted from the structured section in the lower left corner of Figure 4, fibre sections of 25 cm in length and longer were experimentally found to be single-moded by performing the usual tests for single modedness. However, when the fibre was cut back to 5 cm, the same core was found to support more than one mode, as indicated by the observation of interference between different modes in the near field pattern. To our knowledge this is the first time that both single and multi-mode behaviour has been associated with the same fibre at the same wavelength, and illustrates the somewhat ambiguous meaning "single modedness" in holey fibres.

4. MODELING RING STRUCTURED MOFS

We used a development of the effective index approach to model ring structures in MOFs. This approach assumes that all features in the structure are of a size comparable to, or smaller than, a wavelength of light. Inclusions of material of a different refractive index to that of the matrix can be used to form a composite material which can be approximated by a homogenised or effective medium. Rings of holes can therefore be modelled as rings of different refractive index- ie: the conventional Bragg formalism can be employed. Once the average index profile is calculated, the guided modes can be found using Chew's method [10]; an exact method for finding the modes of circularly symmetric fibres.

The refractive index n_{av} of the homogenised material is an average of the refractive indices of the inclusions n_{inc} and the matrix n_{matrix}, weighted by the filling fraction f of the inclusions, which in general satisfies [11]

$$\left(\frac{f}{n_{inc}^2}+\frac{1-f}{n_{matrix}^2}\right)^{-1/2} \le n_{av} \le \sqrt{fn_{inc}^2+(1-f)n_{matrix}^2}. \qquad (1)$$

The light in the fibre propagates in a direction almost parallel to that of the air channels. Therefore the relevant quantity that determines whether the holes are resolved, i.e. whether averaging is justified, is not the wavelength itself. It is the scaled reciprocal of the radial wavenumber $2\pi/k_r$ (with k_r the component of wavevector in the radial direction, perpendicular to the holes), which is much larger than the wavelength. Based on this argument, nearly arbitrary index profiles can be constructed in microstructured fibres. Applying the averaging to the ring structured fibres means that each ring of holes will effectively behave like a homogeneous ring of refractive index lower than that of the polymer. An advantage of using holey ring structures, apart from the flexibility in the structure, is the large range of refractive indices possible. The maximum air-filling fraction obtainable using a ring of holes occurs when the holes are just touching, which corresponds to a value of 0.79 for the entire ring. Using Eq. (1) for our fibre material (PMMA) with a refractive index of 1.5 in the visible, this corresponds to an index difference of about 0.4. This index contrast is much larger than index differences obtainable in silica fibres by processes such as modified chemical vapour deposition (MCVD).

The average index of each layer can be adjusted by varying the size, shape and spacing of the holes in each ring. The shape of the index profile versus radius associated with each ring depends on the hole size and shape. For example, a ring of circular holes will result in a smooth graded index profile. Rings of annular shaped holes or many closely spaced rings of small holes will result in a step-index profile for each ring. Obviously the latter can be used to achieve much higher air-filling fractions and hence higher index contrasts.

Average index models have been applied to microstructured fibres with an hexagonal hole structure with some success. Commonly the entire microstructured cladding is replaced with an averaged cladding of uniform index which allows rough approximations of some of the optical properties to be calculated [1]. The average index model presented here retains more information about the microstructure than previous models since we take only an angular average, which leaves the radial structure intact.

The average index profile for a particular hole structure is found by averaging the refractive index over 360° for fixed values of the radius. The upper and lower limits of Eq. (1) were used to calculate the average index for each radius as well as just the arithmetic mean of the refractive index, which is given by:

$$n_{av} = fn_{inc} + (1+f)n_{matrix} \qquad (2)$$

To check the validity of the Bragg fibre approximation, we also modeled the ring structured MPOF using the multipole method, which allows us to compare the approximate average index model to the calculations for the exact structure.

The structure of the modeled fibre (on which the optical tests were subsequently conducted) consisted of holes of 0.7 μm radius in the first two rings and 0.6 μm holes in the third ring. The radii of the three rings were 2.9, 5.8 and 8.5 μm – the 0.2 μm difference in radius between the 'perfect structure', with the third ring at 8.7 μm radius, and the real fibre dimensions is caused by the drawing process. The hole size and spacing is of the order of 1 μm, which is sufficient for the average index model, since it is much smaller than the scaled reciprocal of the radial wavenumber as mentioned before. The average index calculated for the structure is presented in Fig. 5. Both calculation methods assumed a lossless matrix of index n = 1.4897 for PMMA at 632.8 nm, corresponding to the wavelength used in the experiments.

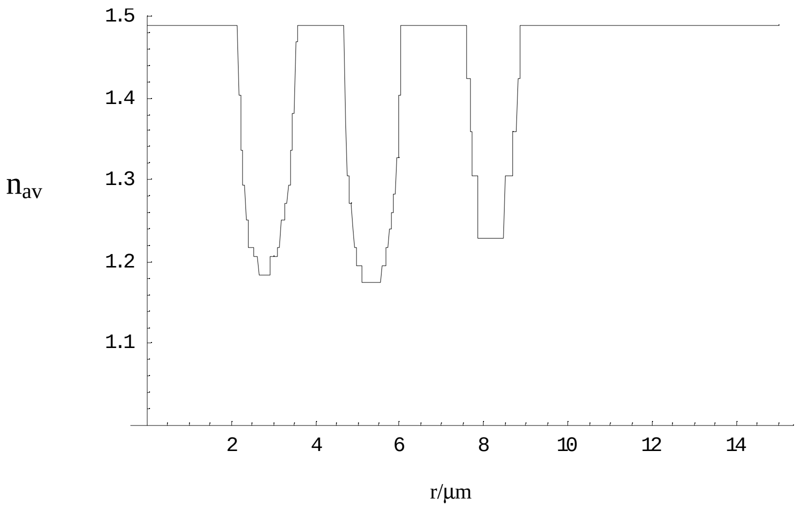

Figure 5. The average index profile calculated for the structure described in the text. The averaging method used was to take the arithmetic mean of the refractive index over 360° for fixed values of the radius. This gives a value for the average between the two limits of Eq. (1). The average index profile is constructed out of 40 layers.

The results of both modeling techniques for this fibre are given in Table 1. In the case of the multipole method, values of the n_{eff} of the modes, as well as the confinement losses are presented for the structure with only the inner ring of holes included and with the inner two rings included. The modeling was limited to the inner two rings of holes due to the large amount of time that would be required for the calculations of the full three ring structure. There was a large decrease in confinement loss when the second ring was included in the calculations. However, the inclusion of the second ring of holes had a negligible effect on the n_{eff} values of the modes. The effect of the third ring on n_{eff} would be even smaller given the lower mode amplitudes at the location of the third ring.

	Multipole Method				Average Index Model
m, Mode Class	1 ring of holes		2 rings of holes		Effective index, n_{eff}
	Effective index, n_{eff}	Loss [dB/m]	Effective index, n_{eff}	Loss [dB/m]	
1, HE	1.486371	17.2087	1.486371	0.0019	1.486033
0, TE	1.481384	135.4567	1.481376	1.4798	1.480501
2, HE	1.481295	185.7771	1.481286	2.7421	1.480370
0, TM	1.481240	236.5710	1.481222	7.2744	1.480272
1, HE	1.474784	1636.000	1.474818	56.575	1.472973

Table 1. Mode class and effective indices of the first five modes as calculated by the multipole method and the average index model, using the arithmetic mean of the refractive index.

For the average index calculations n_{av} was calculated using both limits in Eq. (1) as well as the arithmetic mean of the refractive index. Differences in the values of n_{eff} of the modes for the three cases were found to be of the order of 10^{-4} and always smaller than the difference between the average index model n_{eff} and the values of n_{eff} calculated using the multipole method. Therefore only the results for the arithmetic mean are presented in Table 1. The modes predicted by the two models when ordered by effective index firstly agreed in class (where modes in the same class have the same dependence *m* on azimuthal angle, using notation as in [14]) and secondly in the values of the effective indices (with differences of order 10^{-4} to 10^{-3} for the higher-order modes). This is a strong indication that a microstructured fibre with holes positioned on concentric rings shows similar behaviour to a cylindrically layered structure.

The confinement losses of the modes were also calculated with both the average index model and the multipole method (the latter again limited to two rings of holes). The results for the multipole method are included in Table 1. Unsurprisingly, the losses calculated with the two methods do not agree. The average index model predicts confinement losses many orders of magnitude lower than the multipole method. This is because in the microstructured fibre the main loss mechanism is the leakage of light through the high index paths in between the holes. This leakage route does not exist in the angularly averaged index fibre, where all holes are replaced by closed rings. The loss calculated by the average index model is that which would arise from tunnelling, and hence is much lower.

The confinement losses calculated by the multipole method show that there is one mode with very low losses (0.0019 dB/m). This is the fundamental mode that was observed experimentally in the longer lengths of fibre (25 cm and longer). The next three higher-order modes have a three orders of magnitude higher loss. Although these losses are not large enough to preclude transmission in those modes over 25 cm, we believe that the losses in the fabricated fibre are much larger than the calculated values due to deformations and fluctuations in the fibre structure, and/or due to scattering from imperfections on the hole surfaces. These effects would affect the higher-order modes more than the fundamental as the higher-order modes are more leaky and would have larger amplitudes at more holes. These effects could increase the loss by an order of magnitude, which explains why the higher order modes were not observed in transmission through 25 cm of fibre. However, as discussed previously, when the fibre was cut to 5 cm in length, multimode interference was observed in the near field.

5. THE PROMISE AND SIGNIFICANCE OF MPOFS

The likely impact of MPOFs will be determined by the degree to which they are able to match or surpass the performance of competing technologies. In this respect, a key parameter will be the minimum optical loss that can be obtained. In conventional POFs, the dominant loss mechanisms are material absorption and scattering. The best current figures have been obtained using the CYTOP material (commercialized as Lucina™) produced by Asahi Glass. This is a fluorinated material, having no Carbon-Hydrogen bond or crystallinity, and shows minimal absorption losses within the visible and near Infra-Red.

The intrinsic losses of this material have been characterized by White et al. [12]. In undoped CYTOP they report a scattering loss of 5.2 dB/km at 850 nm, and 0.95 dB/km at 1300 nm. In 10% doped CYTOP this increases to 9.9 dB/km at 850 nm, and 1.8 dB/km at 1300nm. In general, scattering is associated with local variations in dopant concentration and in molecular weight of the polymer sample, which in conventional POFs cannot be easily controlled. Asahi's own analysis [13] of the loss affecting the material shows that at 850 nm the total loss of 17 dB/km comprises 13dB/km due to scattering, 4 dB/km due to structural factors, and negligible absorption. The origin of the "structural" loss is not discussed. At 1300nm, they find that the total loss is 16 dB/km, comprising 2 dB/km for scattering, 10 dB/km for absorption and 4 dB/km for structural factors. At 650 nm the total loss of 47 dB/km is dominated by scattering (41 dB/km).

In MPOFs, variations of dopant concentrations will not be an issue, as the sample need not be doped, although the polydispersity and any other material variability may remain problematic. For MPOF to be competitive with conventional materials based on CYTOP, the losses associated with the hole structure must be similar to, or less than, those associated with variations in dopant concentration in conventional POFs. From the figures presented, it is unclear exactly what is the appropriate figure to attribute to scattering losses due to the dopant, but we may take the figure of White et al. as a useful benchmark, and ask whether or not it is reasonable to aspire to reducing the losses associated with the hole structure to about 5 dB/km.

Without detailed further work this question clearly cannot be answered definitively. Some indication of the answer however may be inferred by consideration of glass holey fibres. The current best conventional glass fibres have a loss of some 0.15 dB/km. This figure includes minimal absorption, of which the most problematic is the OH band at 1385 nm, and Raleigh scattering, which is intrinsic even to pure silica. In solid core glass holey fibres, neither of the existing loss mechanisms is likely to be substantially reduced. Rather, the loss figure may be increased by mechanisms such as interface scattering, longitudinal and transverse variations in the structure, and surface impurities including the ingress of water.

Glass holey fibres have not had the benefit of the long optimization and development period that conventional glass fibres have had, and as yet it unclear what their lowest achievable loss will be. The best current figures are 3.2 dB/km at 1550nm, and 7.1 dB/km at 850 nm [14] obtained by Kubota et al. This suggests that careful control of the manufacturing process can produce the surface smoothness and structural regularity that reduce purely structural losses to a figure comparable to the 5 dB/km figure suggested earlier as a benchmark. In other words, there is cause for cautious optimism that solid core MPOFs may be able to match or even reduce losses compared to conventional POFs, making them a viable alternative to conventional POF for short-haul data transmission.

Using MPOF technology we can readily produce single-mode polymer fibres- a feat that is difficult with conventional POF technology- but we can also produce arbitrary refractive index profiles, by varying the hole structure. Such profiles could for example include the graded index profile multi-mode MPOF. An example of such a design, based on the ring structure approach [7] is shown, together with its index profile, in figure 6.

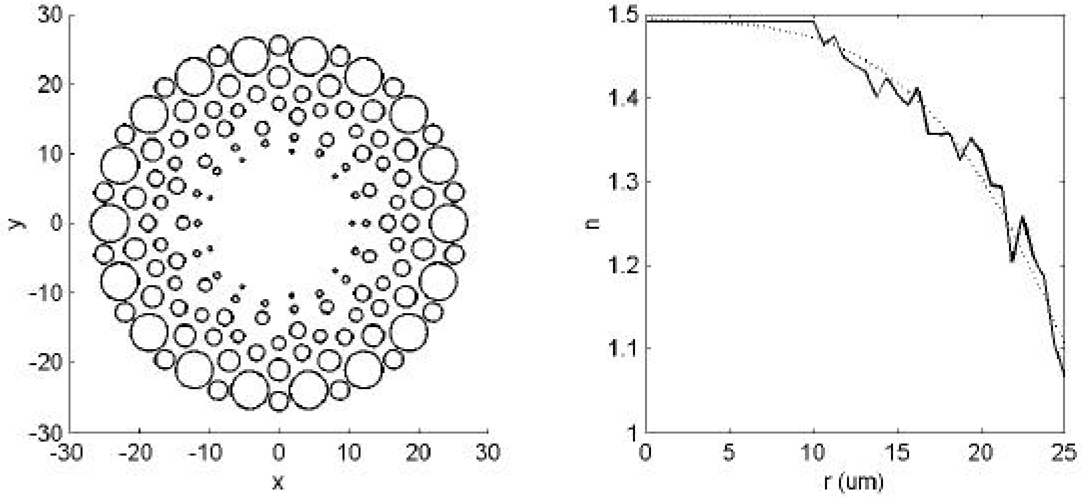

Figure 6. A MPOF graded index design (left), and its refractive index profile (right).

For device applications, MPOFs have a number of potential advantages over glass holey fibres. Microstructured optical fibres fabricated in glass have generally been made by a capillary stacking technique, which results in a hexagonal packing of the holes. The many processing options available in polymers, including casting, casting around capillaries, extrusion etc as well as thermally fused capillary stacks mean that potentially a much larger range of hole structures is available. In addition, drawing of polymer fibres causes an alignment of the polymer chains, which protects the hole structure from collapse and deformation. This means that the drawing process is more robust, and may make it easier to produce non-circular holes, and potentially band-gap fibres, than is the case for glass.

Polymers can be tailored in terms of composition to a much larger degree than glass fibres. Doping options for glass are limited by the need to avoid phase separation, and use of materials that do not decompose at glass processing temperatures (about 2000°C). In polymers, the low processing temperatures (100-250°C) mean that organic materials such as dyes or non-linear chromophores can be easily included without decomposition. In addition to doping, the polymer structure can be modified by grafting to allow large mass fractions of the desired material. Surfactant techniques also allow relatively large quantities of inclusions to be added. Examples of the types of materials that could be used in MPOF are: polymers with enhanced non-linearities, electro or magneto-optic effects, metallic or rare-earth inclusions, birefringent materials such as liquid crystals, photorefractive and photochromic materials, dyes, polymers used in the detection of particular compounds and porous materials. The polymers can be specifically designed to allow the fabrication of particular fibre-optic components based on MPOF.

One feature that is unique to microstructured fibres is the possibility of producing a photonic bandgap, which allows optical transmission in air. Air guiding fibres in glass were first produced at the University of Bath [3] but long lengths have proved hard to produce. We believe that the chain orientation effects in polymers, which help to preserve the integrity of the hole structure, mean that it may be easier to produce the required structures in polymers. We have begun working on air guiding MPOFs. An example of one the fibres we have produced is shown in figure 7. Initial experimental results on air-guiding MPOFs are extremely promising.

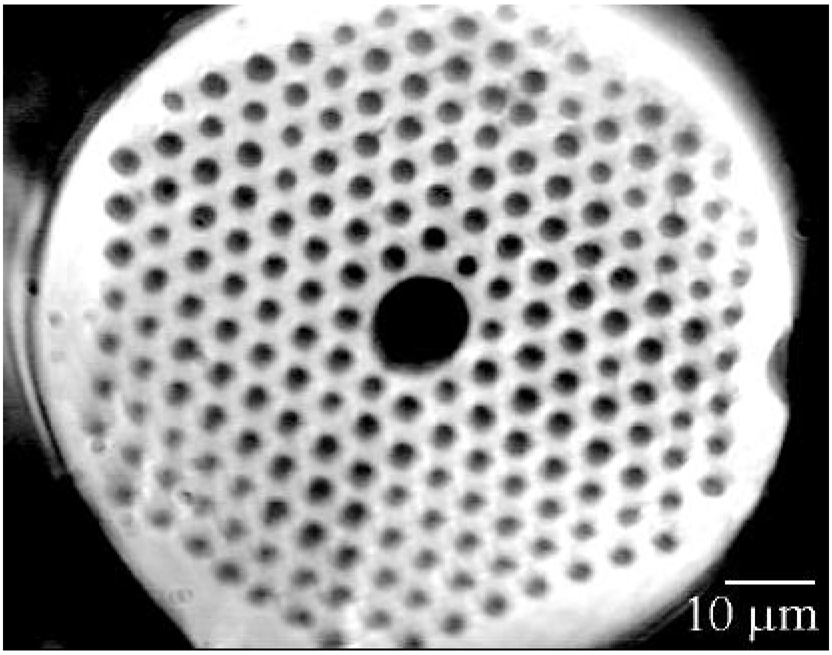

Figure 7. An example of an MPOF fabricated for photonic band-gap effects.

The possibilities of MPOF therefore encompass a large range of potential applications, from short haul data transmission to devices and air guiding fibres. However, challenges remain, including a better understanding of loss mechanisms, and maintaining the integrity of the hole structure for air guiding fibres- particularly for long lengths.

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