Bandwidth and loss measurements of graded-index microstructured polymer optical fibre

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The first bandwidth measurements of graded-index microstructured optical fibres are presented, demonstrating that this novel fibre geometry can provide high-bandwidth multimode polymer fibres without the need for complex doping techniques as with conventional polymer fibres.

Introduction: Microstructured polymer optical fibres (mPOFs) have been developed recently [1–3]: polymer fibres in which the guiding of light is achieved by a pattern of microscopic air holes that run down the entire length of the fibre, similar to photonic crystal fibres (PCF) [4]. The combination of this guiding mechanism and the use of a polymeric material offers new opportunities to enhance the functionality of polymer fibres and to provide specific devices for e.g. data-communication, sensing and imaging applications [5, 6].

Multimode graded-index polymer optical fibres (GI-POF) have been previously developed for data-communication applications, providing thick flexible fibres with high bandwidth and large spot sizes for easy installation in local area networks. However, the technology behind conventional GI-POF is very complex and costly, since a polymerisation process that produces a near-perfect parabolic index profile is required for efficient compensation for the modal dispersion [7].

PCFs are beginning to receive attention for high-bandwidth communication, but only a six-hole structure [8] and a conventional hexagonal hole arrangement [9] have been considered in glass PCF so far. In this Letter we report on the bandwidth and loss characteristics of a multimode microstructured optical fibre with a complex hole structure fabricated from polymer material.

It has been shown that, for sufficiently small hole structures, the microstructure in the fibre remains unresolved by the light, and the whole structure can be approximated by an effective refractive index profile. This has been explored in a previous paper, in which mPOFs with multiple depressed-index rings were presented [2]. Using this average-index effect, we have designed a large-core multimode graded-index mPOF (GImPOF) by using a graded hole structure [3]. As can be seen in Fig. 1, the hole diameters increase with distance from the fibre centre, so that the azimuthal average provides an approximation to the parabolic graded-index profile to compensate for modal dispersion. Note that any problems associated with dopant diffusion are now eliminated, offering advantages for high-temperature POF applications, especially in combination with polymers with a high glass transition temperature.

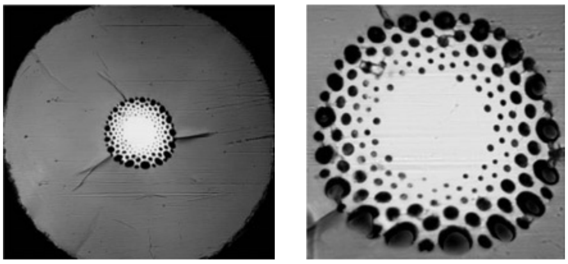

Fig. 1 *Optical micrographs of multimode graded-index microstructured polymer optical fibre (GImPOF) with core diameter of 135 μm and outer diameter of 520 μm*

Fibre fabrication: A range of different fabrication methods is available for mPOF preform fabrication, including extrusion, drilling, casting or injection moulding [1]. The GImPOF shown in Fig. 1 was drawn from a 70 mm diameter PMMA preform rod with 216 holes of varying diameter (1.2, 1.5, 2.0, 2.5, 4.0 mm) drilled into it. This preform was stretched to 8 mm diameter, and inserted into an outer sleeve of 15 mm diameter and fused [10]. The sleeved preform was then drawn to fibre of 520 μm diameter, with a core region of 135 μm diameter as measured by the distance between the opposite edges of the outermost holes (the distance between the innermost holes is 65 μm). Fibre diameter uniformity of ±4 μm is achieved over tens of metres by a feedback control loop between the capstan speed and the fibre diameter monitor.

Fibre transmission losses: We have studied the impact of various stages in the fibre production process on the loss of the fibre. Fig. 2 shows the measured transmission losses of a series of GImPOFs labelled A–F fabricated under different conditions, as listed in Table 1. The material loss curve G is included, showing the strong material absorption peaks near e.g. 725 and 900 nm, associated with a PMMA-based material.

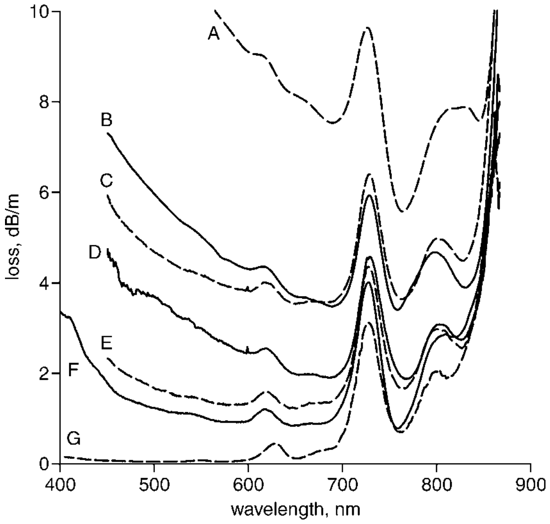

Fig. 2 *Measured transmission losses of graded-index polymer optical fibres labelled A–F as fabricated under conditions listed in Table 1*

Table 1: Description of graded-index microstructured polymer optical fibres as presented in Fig. 2. Note that fibre F is shown in Fig. 1

	Cutting fluid	Water flushed	Sonicated	Fibre annealed	Sleeved
A	Regular	no	yes	yes	no
B	Regular	no	no	yes	no
C	Regular	yes	no	yes	no
D	Regular	yes	no	no	no
E	Regular	yes	no	no	yes
F	Synthetic	yes	no	no	yes
G	PMMA loss data based on standard SIPOF [11]				

The losses were measured by launching white light into at least 5 m of GImPOF with a 25× microscope objective, stripping off the cladding modes and imaging the output onto the detector of an optical spectrum analyser with a 5× objective. The fibre is cut forward in steps of 50–100 cm, and the recorded spectra are normalised to the shortest length (never shorter than 1 m to ensure independence of launching conditions).

Table 1 lists the different stages involved in the fabrication process for the fibres labelled A–F. Firstly, the cutting fluid used in the preform drilling is either a white-coloured oil-based emulsion (‘regular’ fluid) or a clear semisynthetic cutting fluid. In some cases, the preform is flushed with water in a closed circuit for three hours to wash out any contamination. In one case (A) the preform was sonicated for 10 min in a hot water bath. After drawing, the fibre is either annealed at 80°C for 30 min to partially relieve the stresses (this facilitates cutting of the fibre) or left unannealed. Finally, the fibre is either drawn directly from the 70 mm diameter preform (in two stages), or sleeved in a 15 mm tube at the intermediate preform stage, as described previously.

The lowest loss obtained is 0.80 dB/m at 760 nm and 0.87 dB/m at 650 nm for GImPOF (F). Note that the material losses at those wavelengths are 0.72 and 0.15 dB/m, respectively, indicating that the use of higher quality base material will enable a significant further loss reduction. Fibre F was fabricated using synthetic cutting fluid, which provided a 28% loss reduction (see change from E to F), using water flushing of the preform, which provided a 22% loss reduction at short wavelengths (B to C), avoiding sonication which can increase the loss by 200% (B to A), avoiding annealing of the fibre, which can cause a 40% loss increase (D to C), and sleeving the fibre, which provided up to 50% of the loss reduction (D to E). The latter is the most significant loss reduction (as compared to the cutting fluid and water flushing), and is attributed to a significant reduction in the microbending losses [12]. (We have observed that even relatively large deformations of the hole structure have little influence on the transmission losses.).

The remaining loss in the fibre is partially attributed to scattering (as indicated by the λ^{-4} dependence) originating from surface roughness as caused by the drilling process and/or from residual micro particles on the hole surfaces (an analysis of the cutting fluid after drilling showed PMMA microparticles of the order of 0.1 to 2 μm diameter) [13]. In addition there may be ingress of chemical impurities from the cutting fluid that are not flushed out, microbending losses could potentially be reduced further, and some confinement loss is expected to be present, which can be reduced by adding holes to the outer rings of the structure.

Bandwidth measurements: The effects of mode coupling in GImPOF are very strong: we determined the equilibrium length for mode mixing by launching with a low NA and noting that the (larger) output NA was independent of the launching conditions down to fibre lengths of the order of 10 cm. Therefore the standard differential mode delay (DMD) measurements could not be performed [14]. The bandwidth of the fibre was measured by recording the pulse broadening in 10 m of fibre as compared to 1 m. The measurement setup consists of the following components [14]: a laser source at 653 nm with a spectral width of 3 nm and a FWHM pulse duration of 60 ps (PicoQuant PDL800); a pulse generator with 5 ps time resolution, including a delay line (Stanford Research Systems DGD535); and a streak camera based detector with a time resolution less than 10 ps (Hamamatsu OOS-01/VIS). By changing microscope objectives and apertures, the launching conditions could be modified easily. The numerical aperture was varied from 0.1 to 0.33, and the spot diameter from 20 to 200 μm. The pulse broadening was found to be less than 30 ps using full-mode excitation, corresponding to a bandwidth in excess of 4 GHz in 9 m, which translates to a bandwidth greater than 2.4 Gbit/s in 100 m (due to the strong mode mixing the bandwidth scales as $L^{0.5}$ [11]). This is of the same order of magnitude as bandwidths achieved in conventional GIPOF [7], which is an encouraging result, noting that the measurement is only a lower limit due to the experimental limitations, and that no optimisation of the microstructure has yet been attempted.

Conclusions: We have reported substantial loss reductions in the transmission of graded-index microstructured polymer optical fibres through detailed analysis of the fabrication procedure, and identified contamination and microbending as major sources of loss. The best fibres were shown to have a loss of 0.80 dB/m at 760 nm and to provide a high bandwidth data transmission capacity in excess of 2.4 Gbit/s in 100 m. Much room for improvement remains, however, both in terms of loss and bandwidth, which is the subject of ongoing work.

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