

Future Directions for Microstructured Polymer Optical Fibres

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ABSTRACT

Microstructured Polymer Optical Fibres [MPOF] were first made in 2001, and subsequent development has aimed at exploiting the material and design opportunities they present. Most effort has been focused on developing approaches for high bandwidth MPOF, and investigating the properties of multimode microstructured fibres. We also consider new applications in endoscopy and photonic interconnects, as well as the use of organic dopants in MPOF.

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

INTRODUCTION

Microstructured polymer optical fibres [MPOF] occupy an unusual position within the family of optical fibres. Conventional polymer optical fibres [POF] are generally used in applications where the mechanical properties, such as flexibility and connectivity, are more important than optical properties such as loss. These fibres have large cores, to make connection simpler, which makes them massively multi-mode. By contrast, one of the most impressive features of microstructured fibres is their ability to be “endlessly single-mode”. Indeed, the difficulty in producing single-mode POF has constrained POF from moving more strongly into a number of areas, such as sensing, where their tunable material properties would produce a natural advantage.

This position helps to clarify future directions for MPOF. If it is to move into the area conventionally occupied by POF, we need to develop approaches to microstructured fibres that encompass multi-mode operation, something that has not previously been considered. Similarly, exploiting the material properties of polymers may redefine some POF applications. There are also emerging applications where the microstructure can be manipulated to produce new types of fibre, for example to improve endoscopy.

MULTIMODE MPOF FOR HIGH DATACOMM APPLICATIONS

Approaches to high bandwidth fibres

There are a number of possible approaches to multimode MPOF. Conventional POF for high bandwidth applications uses a graded index approach to enhance its bandwidth performance. This approach has been used very successfully in conventional POF, with 2.06 GHz transmission being observed over 150 m in a PMMA based graded index POF [1]. Unfortunately however, obtaining the desired graded index profile is challenging and relatively costly. There is no simple generic method that can be employed, analogous to the vapour deposition process for silica fibre.

One alternative approach is therefore to use microstructure to produce a graded index. Air/polymer microstructured fibres are conceptually different to conventional POF because they suffer from confinement loss - due to the tunnelling of light through the bridges between the holes. A more conventional structure could be produced using a polymer-in-polymer fibre. In such a fibre, the high index core would be completely surrounded by a lower refractive index polymer, with the filled microstructure serving to produce a gradation in the cladding index. Because the guidance method in these fibres is conventional, they do not suffer from confinement loss, and effectively can be considered simply an alternative method of producing graded index POF.

Theoretical studies [2] indicate that such fibres may have bandwidth properties that are comparable to those of conventional graded index POF. Techniques such as co-extrusion might provide a suitably economic fabrication process. Prototyping of these fibres however is at an early stage, and their high attenuation has so far precluded measurements of their optical performance.

The development of a low loss fabrication process for polymer-in-polymer microstructures would be valuable indeed, and allow the development of new types of fibres. The use of multi-core POF has long been known to reduce dispersion by reducing the number of guiding modes [3]. A more subtle effect allows the design of fibres with exactly zero modal dispersion [2]. The design uses closely spaced single-mode step-index cores which maximize the coupling between nearest neighbour cores at a particular wavelength. This effect is possible because the coupling coefficient is not a monotonic function of wavelength. For small wavelengths, coupling does not occur between the cores because the light is too tightly confined. Similarly for large wavelengths, the fundamental mode is so poorly confined that the power in the cores approaches zero. In between these extremes there is a "Goldilocks" wavelength for which the coupling is maximized. At this wavelength, the velocities of all supermodes of the fibre are equal.

An alternative approach is to use a polymer/air microstructures to produce a graded index MPOFs [GIMPOFs]. Such fibres are conceptually distinct from polymer-in-polymer fibres because they necessarily have confinement loss. For single-mode microstructured fibres this is not problematic as this can be reduced to an arbitrarily low level by increasing the number of rings of holes. It is less obvious however how a massively multi-mode fibre will behave in this context.

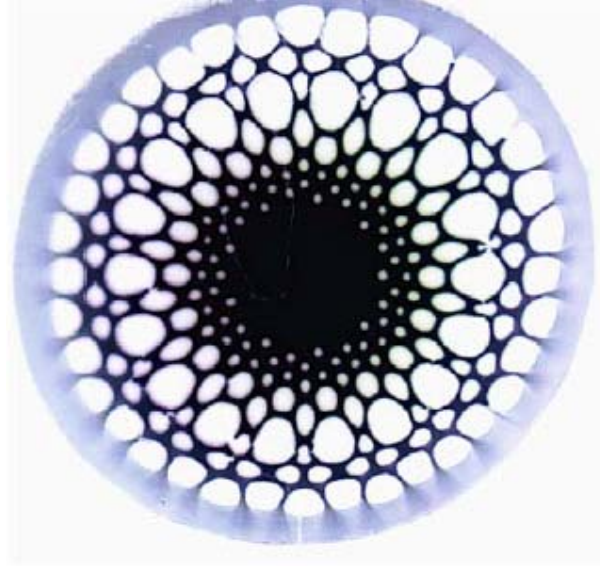


Figure 1. A 250 μm diameter graded-index MPOF with a bandwidth of 4.2 Gbits/sec over 100 metres

Describing multimode behavior

One of the key concepts used to describe multimode behaviour is that of an *equilibrium length*. This is defined as the minimum fibre length required for the power distribution between the modes to equilibrate through mode-mixing, so that the output becomes independent of signal launch conditions. The situation is similar in the context of microstructured fibres, except that here the differential mode attenuation may vary more substantially than in conventional fibres. Mode-mixing has implications both for loss and bandwidth. It allows energy to be transferred to high loss modes, but also reduces pulse spreading, by spreading power spreading over both fast and slow modes.

Mode-mixing is a stochastic process, associated with imperfections in the fibre. These imperfections include such processes as scattering and microbending. The role of imperfections in determining loss and bandwidth behaviour highlights the role that fabrication may play in determining performance, and the need for a concurrent engineering approach to be taken towards fibre design.

Power diffusion between modes in a multimode fibre was first studied by Olshansky [4] who proposed a set of master equations:

$$\frac{\partial P_n}{\partial z} - \frac{1}{v_n} \frac{\partial P_n}{\partial t} = -\alpha_n P_n + \sum \kappa_{m,n} (P_m - P_n) e^{-(\beta_m - \beta_n)^2 L_c^2}$$

Here P_n , v_n , α_n and β_n are the power, group velocity, attenuation and propagation constant of the n-th mode, respectively. L_c is the correlation length of the random perturbations, while the coupling coefficients $\kappa_{m,n}$ depend on the precise overlap of the transverse spatial distribution of the perturbations with the modal intensity profiles. This description assumes that each perturbation is described by a Gaussian correlation function and that all perturbation sources have the same correlation length, although the approach can be easily generalised to cover multiple correlation length scales. The exponential factor implies that the coupling between modes rapidly decays with the difference in propagation constants and thus only coupling between adjacent modes need be retained.

The time independent, or steady-state, version of the master equations has a complete set of orthonormal eigenfunctions or equilibrium power distributions, each of which has its own unique spatial decay rate. These distributions are indicated via a superscript. The distribution P_n^0 with the smallest decay rate γ^0 is the only stable equilibrium power distribution and any initial power distribution will eventually evolve towards this particular distribution. The distribution P_n^1 with the second smallest decay rate γ^1 is also relevant to the power diffusion and equilibration process.

The equilibrium length L_{eq} depends on the difference between the two smallest decay rates $L_{eq} = (\gamma^1 - \gamma^0)^{-1}$. Once stable equilibrium has been established, the global power attenuation is given by γ^0 , while the global (or effective) average group velocity (v_{eff}) is given by the appropriate weighted average over the stable equilibrium distribution:

$$\frac{1}{v_{eff}} = \sum \frac{P_n^0 P_n^0}{v_n}$$

The (rms) pulse width $\Delta\tau$ grows asymptotically with the square-root of the distance according to:

$$\Delta\tau = \sqrt{2zL_{eq}} \sum \frac{P_n^0 P_n^1}{v_n}$$

Thus, it is the two quantities γ^0 and $\Delta\tau$ which determine the loss and bandwidth of the fibre, while L_{eq} sets the length scale over which power diffusion operates.

This formalism reveals what aspects might be different from established results for conventional POF. Circularly symmetric step-index and parabolic graded index fibres have a well known set of modal degeneracies that cause coupling between higher order modes to be stronger than between lower order modes. These exact degeneracies no longer exist for non-circularly symmetric structures, and a different pattern of near-degeneracies or mode distributions will change the pattern of coupling between high order modes. In fact, the non-circular fibre design may be able to be “tuned” to produce a specified pattern of coupling. Differential mode attenuation in conventional fibres varies over only an order of magnitude or so, whereas in microstructured fibres the contribution of confinement loss to differential mode attenuation can vary over several orders of magnitude. The stable power distribution may therefore be much more strongly skewed towards lower order modes from that in conventional fibres.

The most recent measurements on GIMPOFs indicate that this seems to be the case. As the fabrication process has improved the equilibrium length has *decreased* together with the loss. Our most recent results give a value of approximately 3cm- so short indeed, that it is hard to measure with confidence. The bandwidth of this fibre is at least 4.2 Gbits/sec over 100 metres. The numerical aperture of the fibre was 0.12 with a loss of 0.8dB/m at 760 nm. While this is still high in comparison with other POF, the relatively crude fabrication process currently being used [5] offers considerable scope for improvement, particularly in terms of contamination of the material and surface roughness. We are currently studying the loss mechanisms in these fibres and will publish the results separately. The fabrication process itself will be detailed in a subsequent publication.

IMAGING AND INTERCONNECT FIBRES

High-bandwidth multimode fibres offer the likelihood that MPOFs will move into areas where POF is currently used. However the additional functionality offered by MPOFs make new applications a real possibility.

One of the unusual features of MPOF is that it allows multi-core fibres to be fabricated with relative ease, by stacking capillaries which themselves contain a core and cladding structure, or by producing a monolithic preform in which many cores are defined. This is a much less straightforward process in conventional POF because of the difficulty in maintaining compatible rheologies for the core and cladding materials, particularly for a structure which is not radially symmetric.

These multi-core fibres have the potential to transform both interconnect and imaging applications because they greatly reduce the possible spacing of the fibre cores. Rather than requiring a fibre diameter to space the cores, a single fibre itself can contain multiple cores. Tapering can be used to produce fan-outs.

As confinement loss depends on the number of confining rings of holes, there is a fundamental trade-off to be made between the spacing of the cores and the usable length of fibre. For very short lengths however, the core spacing may be very small. Figure 2 shows an imaging fibre in which the solid regions between the holes act as individual cores. Figure 3 shows how this can transmit an image- in this case the letter “C”.

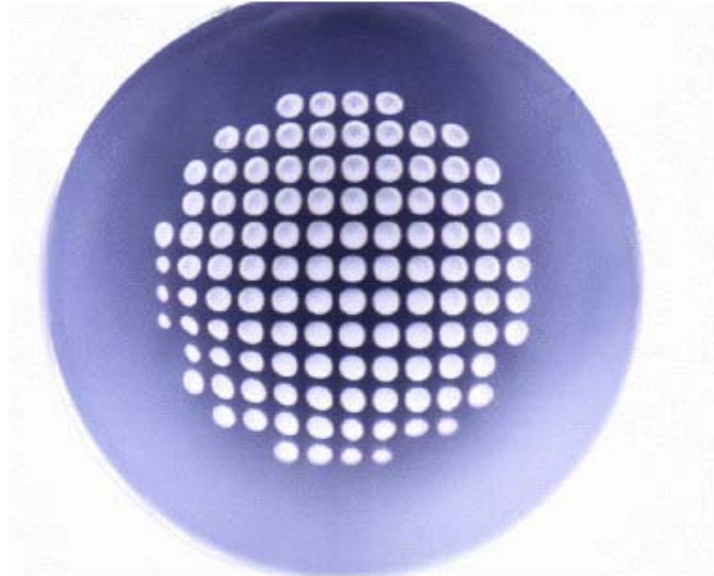


Figure 2. A 800 μm MPOF with 42 μm hole-to-hole spacing developed for imaging purposes.

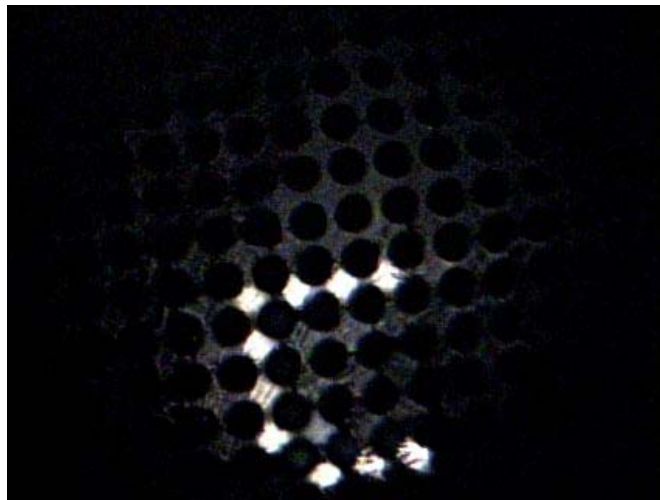


Figure 3. The image of the letter “C” transmitted through cores formed by the solid regions between holes. This kind of transmission is possible for fibre lengths of about 20 cm.

In addition to having applications in imaging, multi-core MPOFs may find applications in photonic interconnect technologies, where they allow the minimum spacing of cores to be reduced dramatically. This may be important for applications where high speed, short distance optical connections are needed, such as between computers or even chip-to-chip.

ORGANIC DOPANTS

We have also begun to explore the use of organic dopants in MPOF. The addition of highly conjugated chromophores to the polymer system may significantly affect the rheology of the draw, so that defining a suitable grafted or co-polymer system may be a lengthy process. We have developed a methodology that allows electrodes to be incorporated into the fibre during drawing. This allows an electric field to be applied across the core region to produce poling. The new methodology allows poling to be rapidly tested in guest-host systems. These do not have the thermal stability to be useful in real devices, but may allow promising chromophores to be identified and proof-of-concept experiments to be carried out.

The technique exploits the very large surface area of MPOFs, and the diffusive processes of glassy polymers. Flushing the intermediate preform or “cane” with a doped solution allows a layer of material to be deposited on the inside of the holes. Subsequent heating of the cane close to its glass transition temperature causes this material to diffuse through the polymer. Whilst care must be taken that the solvent does not damage the cane, either by causing cracking, or dissolving the material, it is possible to use the technique to produce a uniform concentration profile across the core [Figure 4]. Further work on this method will be published shortly.

One area where the technique will be useful is in producing poled doped fibres for the electro-optic effect. We have shown previously [6] that it is possible to incorporate electrodes into MPOF during the drawing process. Given the requirement for molecular order to be thermally stable in this case, a guest-host system is not ideal. However it does allow promising chromophores to be tried out.

In systems where molecular order is not important the guest-host system allows MPOF to be properly tested. By doping MPOF with Rhodamine 6G we have produced a fibre with a gain of 5 dB/m at 570nm using a pulsed doubled Nd:YAG Laser. The spectrum is shown in Fig. 5.

Another system in which molecular order is not important is that of chiral materials which offer the possibility of circularly birefringent or optically active fibres. 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 [7]. Circular birefringence offers a route to making optical fibres that are *polarization maintaining*. Circularly *polarizing* fibres [which allow only one handedness of light to be transmitted] requires the other handedness to be lost. This may either happen because of circular dichroism, or by the appropriate choice of fibre design. We have begun investigating approaches to making optically active fibres, both by doping, and also by developing chiral polymers and copolymers of cholesteryl methacrylate.

It is increasingly clear that the ability to dope MPOF will allow a large number of new applications to be developed, particularly in the sensing, and nonlinear optical areas.

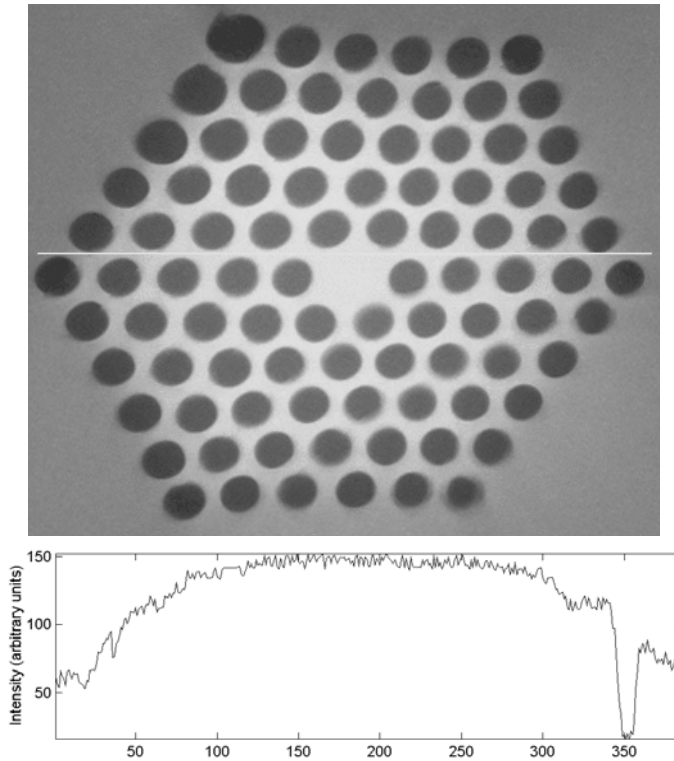
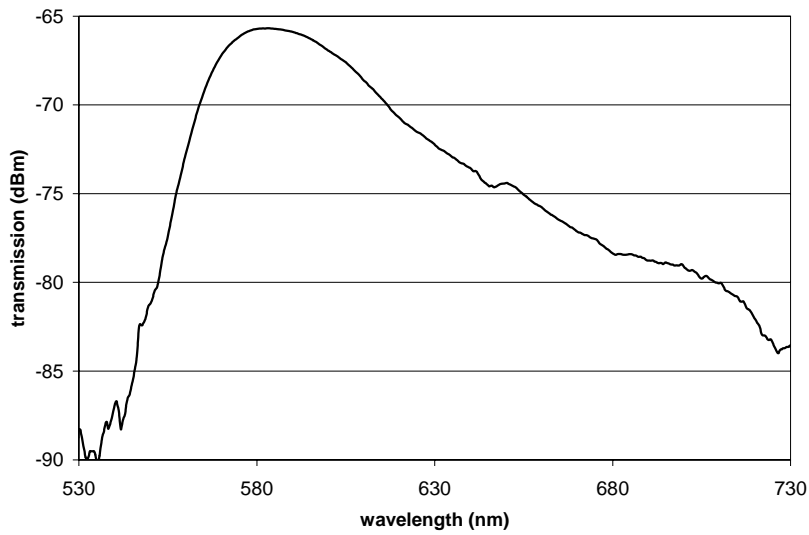


Figure 4.
 An MPOF doped with Rhodamine 6G a). The intensity across the line shown was digitized to illustrate the uniformity of the doping b).



Fluorescence measurement of an MPOF doped with $1.2 \cdot 10^{-3}$ mol/L of Rhodamine 6G.

CONCLUSIONS

MPOFs are emerging as a new fibre platform, in which the material advantages of polymers can be married with the optical advantages of microstructure. The use of a single polymer material frees MPOF from a number of processing issues that have previously bedeviled POF, such as the need to maintain compatible rheologies during the draw process and thermal instabilities due to diffusion. As the guiding properties of these fibres are not due to doping, MPOF has the potential for much higher temperature performance, if made using a suitable polymer.

While the loss of these fibres is still considerably higher than for conventional POF, we have demonstrated that the key advantages of high bandwidth, large core flexible fibres are maintained in MPOF. Further work needs to be done on reducing the loss of these fibres so that they become competitive with rival technologies.

Theoretical work on polymer-in-polymer fibres has also indicated new directions. Doping the polymer matrix, or using novel polymers will allow MPOF to be further developed for applications such fibre lasers, sensing fibres and circularly birefringent fibres.

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