Microstructured Polymer Optical Fibres:
Impact of Imperfections in Design and Manufacture

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Abstract: Surface imperfections in preforms and fibres, and hole deformation during drawing are critical issues to understand, control, eliminate or exploit in the design and manufacture of microstructured polymer optical fibres (mPOF). We review our recent progress.

1. Introduction

Conventional polymer fibres are generally considered for applications where flexibility and connectivity are more critical than loss. For example, multimode graded-index fibre with an approximately parabolic profile and large core area dominates many short-haul applications due to its low cost, ease of splicing and high bandwidths [1]. Likewise, mPOF provide impressive design features associated with the unlimited variety of hole arrangements that can be used to manipulate the properties of the final fibre [2]. In this paper, we look at recent advances in understanding the role played by two types of imperfections: (i) the surface roughness and impurities that occur in both preforms and fibres; and (ii) the deformation of hole shape that takes place during drawing to fibre.

Powerful numerical algorithms exist for both the optical modelling of mPOF and the rheological modelling of the fibre draw process. Here we complement these computationally expensive approaches by focussing on 'rules of thumb' and conceptually based approximations that yield valuable information about the interactions between fibre design and manufacturing.

In Section 2, we discuss a factorisation property for mode-mixing that separates design and manufacturing related parameters. In Section 3, we discuss how the different stages in the drawing process impact on hole deformation. The goal is to obtain an understanding of the relative importance of two complementary sets of parameters: those related to the geometric design of the fibre and those related to its ultimate manufacture.

2. Mode-mixing by surface imperfections

The large bandwidth in most multimode fibres is a combination effect of the minimal dispersion properties of the parabolic profile, mode-mixing due to imperfections and the differential attenuation of the higher order modes. Unfortunately, well-known results about mode-mixing in solid polymer fibres do not apply directly to mPOF. However the coupling coefficients describing power transfer can be obtained from an ensemble averaging of the relevant surface perturbations [3,4] with the typical size of the coupling being given by:

$$\kappa_{i,j} \approx \frac{(n_{polymer}^2 - n_{air}^2)^2}{L_{mixing}} S_{i,j},$$

Note that the geometric design factor $S_{i,j}$ depends only on the arrangement of holes and the mode profiles, while the mixing length

$$L_{mixing} = \frac{16A}{\sqrt{\pi}\eta h^2 k^2 L_c}$$

depends only on the manufacturing parameters. Here h is the rms height of the surface roughness, L_c is the longitudinal correlation length, k is the wave number, η is the degree of correlation of the roughness around the perimeter of a single hole and A is the effective core area. The mode-mixing equations can be solved using a continuous power diffusion approximation to give the equilibrium length and power distribution. If κ and α are the typical size of the coupling and loss for the low-order modes then the equilibrium length, the effective number of modes and the effective attenuation of the equilibrium power distribution are given respectively by:

$$L_{eq} \approx \frac{32}{27\pi^2\kappa},\ N_{eq} \approx \left(\log\frac{\kappa}{\alpha}\right)^2,\ \alpha_{eq} \approx \frac{256}{9\pi^2}\kappa.$$

The geometric design enters into the loss α in a similar way to the expression for coupling given earlier, since many loss mechanisms (eg scattering) can be reinterpreted as coupling to radiative modes.

3. Hole deformation

Hole deformations that are qualitatively consistent with our empirical observations have been obtained by modelling the fabrication process as an isothermal draw of a Newtonian polymer. The basic formalism follows that of Schultz and Davis [5]. It should be appreciated that the drawing process involves the interplay between inertial, viscous, gravity and surface tension based forces. These influences can be combined in terms of several dimensionless numbers (related to the inverses of the Reynolds, Froude and Capillary numbers). The combinations used here are

$$\text{Dimensionless viscosity, V} = \frac{\nu}{WR}$$

$$\text{Dimensionless gravity, G} = \frac{gR}{W^2}$$

$$\text{Dimensionless surface tension, S} = \frac{\sigma}{W^2 \rho R}$$

where W is a characteristic velocity, R is a characteristic radius and g is the acceleration due to gravity. Indicative values are used for the physical properties of the polymer (here PMMA). Thus $\nu = 150\ \text{m}^2\,\text{s}^{-1}$ is the kinematic viscosity, $\rho = 10^3\ \text{kg m}^{-3}$ is the density and $\sigma = 0.04\ \text{kg s}^{-2}$ is the surface tension coefficient. The table below shows representative estimates of these three dimensionless numbers for combinations of velocity (v) and radius (R) that are typical of values that occur in the three stages of the overall fabrication process (ie preform, intermediate cane and final fibre).

	Preform	**Cane**	**Fibre**
W (m s^{-1})	1×10^{-6}	5×10^{-5}	2×10^{-2}
R (m)	3.5×10^{-2}	5×10^{-3}	2.5×10^{-4}
V	4×10^{9}	6×10^{8}	3×10^{7}
G	3×10^{11}	2×10^{7}	6
S	1×10^{9}	3×10^{6}	400

Note that V, G and S are manufacturing parameters that each have the potential to impact on hole deformation. The other critical parameters that could influence the amount of hole deformation are geometric in nature, being the hole sizes and the distance between them.

The force acting on the inner surface of a hole can be approximated by the result for the steady state draw of a single circular hole of radius r in a solid cylinder of radius R:

$$\frac{F}{A} \approx \rho W^2 \left\{ \frac{r+R}{r} S + \frac{4(rR' - r'R)}{(r+R)^2} V + (r' - R')G \right\}$$

where primes indicate derivatives along the draw direction. When dealing with the interaction between neighbouring holes, the geometric factors in front of the three components of the force will be more complicated in form and also include the hole spacing.

The table and the formula reveal that viscosity is always important. However, gravity dominates over surface tension during the primary draw of preforms, and vice versa during the final draw to fibre; particularly for the cases when the fibre is drawn at a slow rate.

4. Discussion

The various judicious approximations above and the identification of key relevant parameters reveal how the manufacturing and design interact. In this context, it has proven possible to isolate the fundamental design parameters from the fundamental manufacturing parameters. The approximations will be compared to detailed numerical simulations. The longer term aim is to develop rapid methods for showing whether the key to improving fibre quality lies predominantly in the design or the fabrication process.

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6. References

1. W. Daum, *et al.*, *POF – Polymer optical fibers for data* communication (Springer, Berlin, 2002).
2. M. A. van Eijkelenborg et al. (2003) “Recent progress in microstructured polymer optical fibre fabrication and characterisation,” Opt. Fibre Tech. **9**, 199-209.
3. L. Poladian (2004) “Modelling surface imperfection induced mode mixing in multimode microstructured fibres” in Conference on Lasers and Electro-optics/International Quantum Electronics Conference, San Francisco, USA, 16-21 May 2004.
4. G. W. Barton et al. (2003) “Characteristics of Multimode Microstructured POF Performance” in Proceedings of Plastic Optical Fibre Conference, Seattle 14-17 September 2003, pp. 81-84.
5. W. W. Schultz and S. H. Davis (1982) “One-Dimensional Liquid Fibers”, J. Rheol. **26**, 14. 331-345.