

# Hole Deformation in Microstructured Optical Fibres

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**Abstract** Hole collapse, expansion and shape change can all occur during the draw process of microstructured fibres. This process is studied experimentally and theoretically.

## Introduction

Hole deformations, both relative size and shape changes commonly occur when microstructured fibres are drawn, as illustrated in Figure 1.

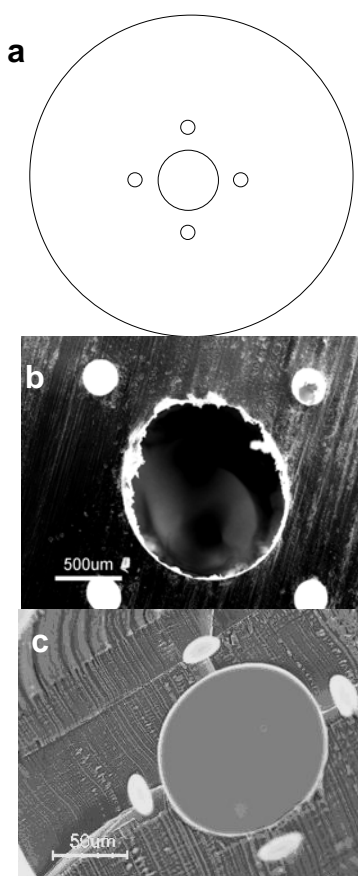


Figure 1: Images of a mPOF preform design a), the resulting cane b) and fibre c). The central hole expands and the small holes contract in the draw to cane. Substantial shape change is evident in the draw to fibre. The diameter of the large hole is 14mm in the preform.

These changes may result in significant alteration of the optical properties relative to the initial design. We have recently used controlled deformation as a means of generating elliptical holes for birefringent fibres [1]. When microstructures are used to generate graded index fibres, hole deformations may substantially affect the resulting profile. Perhaps the fibres most sensitive to distortion however are photonic bandgap fibres, which generally include holes of quite different diameter (the core and the microstructure) in close proximity. As shown in Figure 1, such fibres are prone to dramatic distortions. Since photonic bandgap fibres require a high degree of regularity in their structure the effects of distortion can be catastrophic, and highlight the need for pressurization in drawing this kind of fibre.

The interplay of viscosity and surface tension has been previously identified as determining the degree of hole deformation [2]. Our studies show that distortions can occur even in the absence of surface tension, and differ substantially depending on the nature of the draw process.

## Experimental studies

Most of our studies have focused on Microstructured polymer optical fibres (mPOF), although many aspects of the work are also applicable to similar fibres made from other materials. MPOF are produced using a two-stage draw process [3]. In the first stage a short preform with an outer diameter of between 7-10 cm is used. There is no preform feed, and the draw is akin to a tapering process, using small external force to assist the drop. In the second stage draw, an intermediate preform or "cane" is drawn to fibre. The cane is approximately 1cm in diameter, and is continuously fed.

Over the complete mPOF fabrication process (preform to fibre) there is generally hole collapse of

approximately 35%, although this figure depends on hole size and geometry. Size changes, both contraction and expansion predominantly occur in the first draw process, with of order 5-10% occurring in the second draw. As shown in Figure 1, hole expansion is also possible even in the absence of pressurization; a result which underlines that surface tension is not always a dominant force.

Shape changes can occur in the second draw process when holes of very different sizes are closely spaced, due to the way the net force acting on the hole scales with radius. The net force acting on the hole is approximated in the following section, with the representative numerical values.

The critical factor in determining the degree of deformation is the geometry of the neck-down region, with faster neck-downs resulting in much greater deformations. Studies of the neck-down region also reveal an important difference between the two draw processes. Deformations in the neck-down region of the secondary draw are more important than those of the primary draw because of the continuous nature of the draw. Since all fibre passes completely through the neck-down region in the secondary draw, hole deformations are also passed on, while the primary draw is essentially an elongation. Cross-sections through primary neck-downs show that the same hole may show hole expansion and contraction in different regions.

### Theoretical studies

Hole deformations that are qualitatively consistent with our empirical observations have been obtained by modeling the fabrication process as a Newtonian, isothermal draw. The basic formalism follows that of Schultz and Davis [4]. The drawing process involves the interaction of 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. Table 1 shows representative estimates of

these three dimensionless numbers for combinations of velocity ( $W$ ) 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).

Table 1: mPOF draw characteristics

	preform	cane	fibre
$W/\text{ms}^{-1}$	$1 \times 10^{-6}$	$5 \times 10^{-5}$	$2 \times 10^{-2}$
$R/\text{m}$	$3.5 \times 10^{-2}$	$5 \times 10^{-3}$	$2.5 \times 10^{-4}$
$V$	$4 \times 10^9$	$6 \times 10^8$	$3 \times 10^7$
$G$	$3 \times 10^{11}$	$2 \times 10^7$	6
$S$	$1 \times 10^9$	$3 \times 10^6$	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.

### Conclusions

Experimental and theoretical studies highlight the differences between the primary and secondary draw processes in mPOF. Understanding hole deformations during the draw process will allow preforms and the draw process to be altered appropriately to produce the desired fibre properties.

### References

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