Gas Flow Modelling of Hollow-Core Optical Fibre Evacuation through Laser-Machined Channels in the Cladding

Peter Horak[1], **Kavitha Srinivasan**[1], **Radan Slavík**[1], **Natalie V. Wheeler**[1]

1. Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom

Hollow-core optical fibres (HCF), where light is guided in air-filled holes inside a silica fibre structure, have exceptional guidance properties such as low loss, low optical nonlinearity, and low noise-induced phase fluctuations. HCF nonlinearity and thermoconductive noise [1] could be significantly reduced further, if the fibres could be evacuated and guidance achieved in vacuum. However, because of the small core size, evacuating a HCF from the fibre ends is a very slow process, e.g. it takes over 60 h to reduce the average pressure in a 100 m long fibre with 20 μm core diameter from 1 bar to 0.1 bar (250 days for 1 km length). One way to accelerate fibre evacuation is by machining small holes through the cladding along the fibre length, e.g. through laser ablation [2]. Here we use fluid dynamics simulations to establish the required shape and size of the machined holes and their spacing to achieve given evacuation times.

We have developed a fast numerical method to model the evacuation of the HCF core through a periodic array of cladding holes, as shown in Fig. 1(a). A finite element fluid dynamics simulation is first performed to calculate the flow rate Q through a given hole geometry for a fixed pressure difference of 1 Pa pressure inside and 0 Pa outside in steady state. This flow rate multiplied with the instantaneous pressure $p(t)$ of the core, $Q\,p(t)$, is then used as an outlet in a time dependent simulation of the air flow inside the fibre core. The periodic symmetry of the system along the fibre length is exploited and only one period, indicated by the red rectangle in Fig. 1(a) is simulated. A numerically highly efficient 1D flow simulation method [3] is used, which we have validated against full 2D finite element simulations.

Fig. 1(b) shows calculated flow rates Q for a selection of hole shapes such as cylindrical, conical, and elongated slots. The achievable flow rates can differ by many orders of magnitude. Fig. 1(c) shows the time taken to reduce the average pressure in the HCF core to 10% from initial 1 bar as a function of hole spacing and hole flow rates Q. While this is not high vacuum, such a pressure reduction would reduce optical nonlinearity and phase noise of a HCF by an order of magnitude. We observe that for a given value of hole spacing, a threshold value of Q exists above which evacuation time does not improve. This indicates that evacuation times are limited by the longitudinal flow in the fibre, and not by the flow constriction through the narrow holes. For example, for a hole spacing of 5 m, the evacuation time is around 10 minutes for any $Q > 10^{-15}$ m^3/s which, according to Fig. 1(b), can be achieved by a wide range of hole geometries with openings of ~2 μm. Thus, evacuation time can be reduced by two orders of magnitude or more and only depends on hole spacing and hole flow rate, independent of fibre length.

In addition to fibre evacuation, we have also developed analogous numerical models and analytical approximations for filling optical fibre cores through machined cladding holes either by pressure driven flow or by diffusion, with applications in particular for fibre gas sensing. Experimental efforts are also in progress.

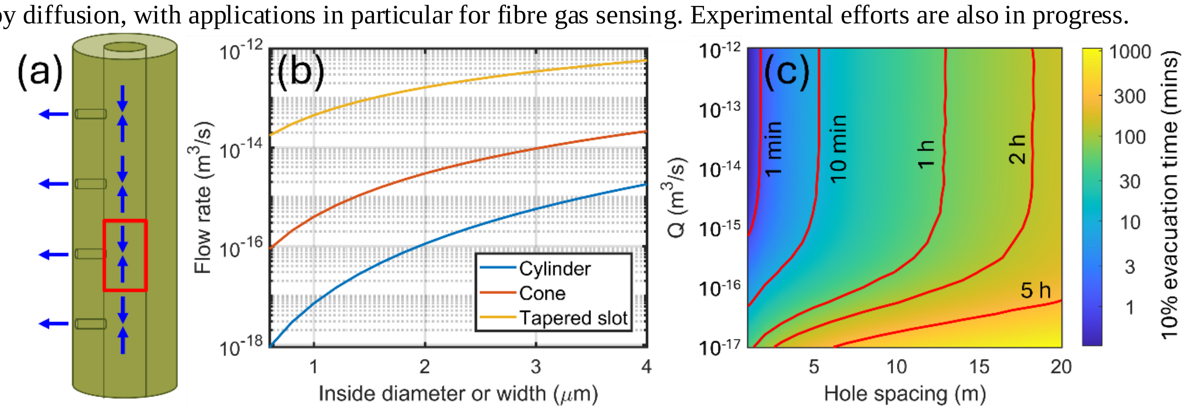

Fig. 1: (a) Schematic of HCF with periodic cladding holes for evacuation of the core. Red rectangle indicates area simulated. (b) Laminar flow rate through cylindrical, conical, and tapered slot cladding holes vs hole width inside core for 1 Pa pressure difference. Cladding thickness 100 μm, fibre core radius 10 μm, outside hole width 20 μm. (c) Time to reach 10% average core pressure (=100 mbar) vs hole spacing and hole flow rate. Note that (b) relates flow rate to geometry of holes.

References

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