Gas Filling and Evacuation of Hollow-Core Optical Fibres through Laser-Machined Side Channels

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***Abstract*—Modifying the gas content inside hollow-core optical fibres can be used for reducing loss, optical nonlinearity, and phase noise, for modifying chromatic dispersion, or for gas sensing. However, filling or evacuating long lengths of fibres through the fibre ends is extremely slow. Here we report on our work on fluid-dynamics modelling of gas flow through laser machined holes in the fibre jacket to determine optimum hole sizes and hole spacings for fast filling and/or evacuation of hollow-core optical fibres.**

***Index Terms*—Hollow-core fibres, gas filling, sensing, fluid dynamics simulations.**

I. Introduction

Hollow-core optical fibres (HCFs) have seen dramatic progress over the last few years and are now the lowest loss fibres that have ever been made [1]. The hollow core of these fibres is usually filled with air at atmospheric pressure but for some applications it would be beneficial to replace the air with other gases or gas mixtures, e.g. for sensing, to evacuate the fibres in order to further reduce optical nonlinearity or thermal phase noise [2], or to pressurise the fibre core for control of chromatic dispersion [3] or propagation loss and modality [4].

However, pressurisation and evacuation times for long HCFs scale proportional to L^2/D^2 [5], where L and D are fibre length and core diameter, respectively. For example, evacuation to 10% of atmospheric pressure takes 60 h (250 days) for a 100 m (1 km) long HCF with 20 μm core diameter. To improve the access to the gas composition and gas pressure inside the HCF, microscale holes or slots can be machined into the fibre jacket by femtosecond laser machining [6], see the scanning electron microscopy (SEM) image in Fig. 1(a) for an example made in our lab [7].

Here we investigate time scales for evacuation and for the diffusion of a dilute gas species into the fibre core for sensing. We perform finite element gas dynamics simulations in Comsol Multiphysics® to determine the size and spacing of an array of laser machined holes along the length of a HCF to achieve realistic evacuation and/or filling times.

A schematic of the setup is shown in Fig. 1(b). We model a simple capillary fibre, i.e. ignoring the glass microstructure of a real HCF, with jacket thickness of 100 μm and a core diameter of 20 μm. We assume a periodic array with spacing S of conically shaped holes with a diameter of 20 μm on the outside of the fibre, and an inner diameter which is scanned. Exploiting the symmetry of the structure, our numerical model is restricted to one period (cf. the red rectangle in Fig. 1).

This work was funded by the U.K. EPSRC under project EP/W037440/1.

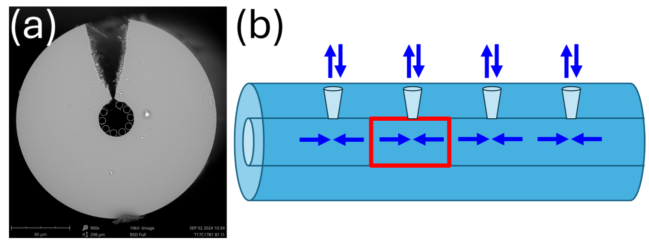

Fig. 1. (a) SEM image of a femtosecond laser machined hole through the jacket of a HCF. (b) Schematic of HCF with periodic array of conical holes in the fibre jacket. The red rectangle indicates the area used in the simulations.

II. Fibre evacuation

We first consider the evacuation of a HCF through the holes in the fibre jacket [8]. The fibre core is initally filled with air at 1 bar. The pressure on the outside of the holes is set to vacuum (0 Pa) at all times.

The simulation is performed in two steps. First the steady state flow through a single hole is simulated using the “Laminar Flow” module in Comsol for a pressure of 1 Pa inside the fibre. From this the volumetric flow rate Q_e is obtained (units m^3/s/Pa). In a second step, the time-dependent one-dimensional gas flow equations [5] are solved using the “Coefficient Form PDE” module of Comsol to simulate the flow along the fibre core with an outlet flow at the position of the hole given by $Q_e \cdot p(t)$ where $p(t)$ is the instantaneous pressure in the fibre at the position of the hole. We consider laminar flow at all times, which is appropriate for pressure decreases down to 1% and covers a large range of applications.

Figure 2 shows the time it takes to evacuate the fibre core from 1 bar pressure down to 0.1 bar as a function of hole spacing S and inner hole diameter D_h. We see that for small hole diameters D_h the evacuation time strongly depends on D_h for constant hole spacing S. In this case, evacuation is limited by the flow through the small holes. On the other hand, for $D_h \gtrsim 1.5\,\mu$m and fixed S the evacuation time becomes constant, indicating that the flow is limited by the

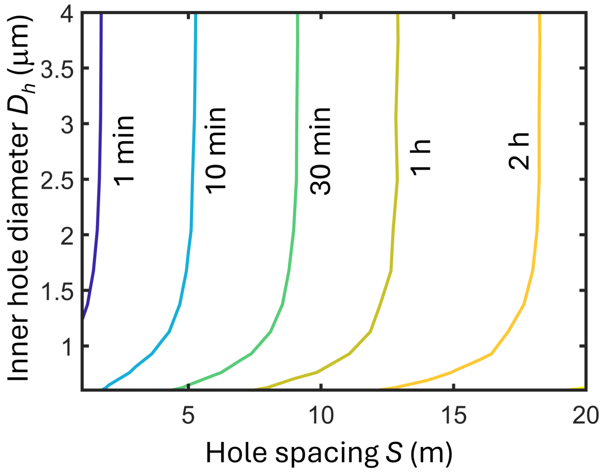

Fig. 2. Time of fibre core evacuation from 1 bar to 0.1 bar vs hole spacing and inner hole diameter of conical holes.

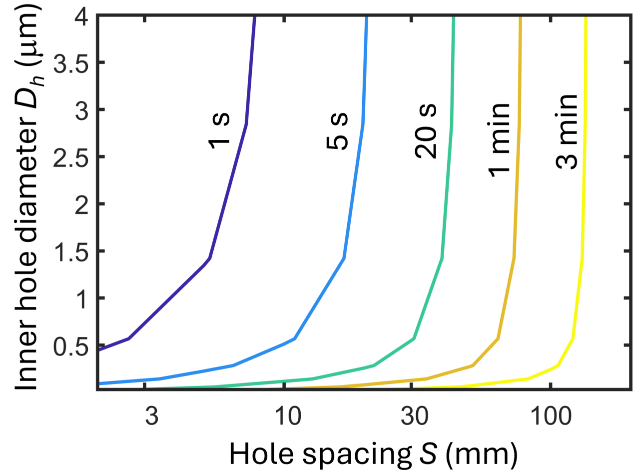

Fig. 3. Time of fibre core filling by diffusion to 90% of final concentration vs hole spacing and inner hole diameter of conical holes.

slow flow along the length of the small fibre core. For the chosen parameters, evacuation times can be reduced to 2 h or even 1 minute for hole spacings of approximately 18 m or 1 m, respectively. The simulations show that only around 10 holes of micrometre size are required over a 100 m fibre length to reduce the evacuation time by two orders of magnitude, from 60 h to around 30 minutes.

III. Fibre filling by diffusion

In the second case we consider dilute gas sensing using the HCF structure of Fig. 1. The HCF is initially filled with pure air at 1 bar. Outside the fibre, a small admixture of methane is present, which from time $t = 0$ starts to enter the HCF through the jacket holes. The process is driven only by diffusion without any pressure gradient.

Similarly to above, we assume that the diffusive flux of methane through the small holes in the fibre jacket is always in steady state for an instantaneous methane concentration difference Δc (in mol/m^3) between the fibre core and the outside gas. The diffusion equation for a conical hole can be solved analytically, giving a diffusive flux (in mol/s) of

$$Q_d = D\frac{\Delta c}{T_j} R_{\rm in} R_{\rm out} \pi \tag{1}$$

where $D = 0.224$ cm^2/s is the diffusivity of methane in air, T_j is the thickness of the jacket, and $R_{\rm in}$ and $R_{\rm out}$ are the inside and outside radii of the hole. The diffusion of methane along the fibre core is then simulated with the "Transport of Diluted Species" module in Comsol in a 2D axisymmetrical geometry with the flux calculated from Eq. (1) used as an inlet boundary condition at the position of the hole.

We define the diffusion filling time as the time it takes to reach an average methane concentration inside the entire fibre core of 90% of the concentration outside the fibre. As diffusion is a very slow process and target detection time of a sensor for trace gas sensing should be in the second to minute regime, we need much smaller spacings S in the mm to cm region compared to the metre scale of Fig. 2.

Figure 3 shows the diffusion filling times versus the inner hole diameter $D_h = 2R_{\rm in}$ and hole spacing S. Again we notice strong dependence of filling times on the hole diameter for very small sizes ($< 1\,\mu$m) where diffusion through the small hole limits the filling times. For larger holes of $D_h \gtrsim 1.5\,\mu$m, similar to above, the hole size is no longer limiting the diffusive flux but the filling times are limited by slow diffusion along the length of the fibre core. In this limit, the filling time becomes independent of D_h for a fixed hole spacing S. Spacings of $S \approx 1$ cm are needed for sensor response times of order seconds, or $S \approx 10$ cm for time scales of minutes.

IV. Conclusions

Controlling the gas content and/or gas pressure in the core of a hollow-core optical fibre enables a wide range of novel applications. Here we used finite element simulations to investigate the gas flow dynamics in HCFs that are filled or evacuated through a periodic array of holes machined through the fibre jacket by femtosecond laser machining. We developed theoretical and numerical models and investigated two sample applications: evacuation of HCF in the laminar flow regime, and filling of the fibre through diffusion by a trace gas species. Our simulations predict that hole spacings of order 10 m for evacuation and of order 1 cm for diffusive filling are required for evacuation times of 1 h and diffusion filling times of 1 s, respectively. In both cases, relatively small holes are sufficient with inner diameters of $> 1.5\,\mu$m.

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