Distributed measurement of hollow-core fibre gas filling and venting via optical time-domain reflectometry

Elizaveta Elistratova, Thomas W. Kelly, Ian A. Davidson, Hesham Sakr, Thomas D. Bradley, Austin Taranta, Francesco Poletti, Radan Slavík, Peter Horak and Natalie V. Wheeler
Optoelectronics Research Centre, University of Southampton, United Kingdom, SO17 1BJ

The gas pressure and composition within a hollow core optical fibre (HCF) are important across diverse application scenarios. For example, it has been shown that the gas pressure inside HCFs immediately after fabrication is sub-atmospheric [1]. When such an 'as-drawn' HCF is exposed to ambient conditions, the air penetrates the core and cladding holes at different rates (due to their different cross-sectional areas), temporarily creating a pressure difference and therefore a transient, gas-induced differential refractive index (GDRI) [2] between the core and cladding holes that modifies the fibre's optical properties. A transient GDRI also occurs when an HCF is intentionally pressurised with gas [2]. GDRI can therefore impact HCF based gas-sensing and purging (unwanted gas species removal), and is an important consideration in as-drawn fibre characterisation. So far this effect was studied via integrating techniques, i.e. measuring the change of the overall fibre transmission over time, without tracing the process along the fibre. However, to fully map the gas flow dynamics and enable comprehensive comparison with gas flow modelling further characterisation techniques are needed. Here, we present a distributed method of observing gas flow dynamics in HCFs via optical time-domain reflectometry (OTDR).

Fig. 1(a) shows our experiment; the OTDR (LOR-200, 1550 nm) is coupled to 450 m of 5-tube nested antiresonant nodeless fibre (NANF, 35 μm core diameter, 0.35 dB/km loss at 1550nm [3]) via an 8°-angled polished solid-core fibre [4]. The HCF's distal end is inserted into a gas chamber. Due to the very low light-glass overlap in a NANF, the OTDR light pulses are predominantly backscattered by the gas in the fibre core [4] and thus the detected signal is approximately proportional to the gas pressure within the core. The initial OTDR trace (0 h), recorded with atmopsheric pressure in the NANF's core and cladding is shown in Fig. 1(b). Fig. 1(c) then shows the progression of the backscattered power with fibre length over 50 hours after delivering 6 bars dry air into the distal end of the NANF via a gas chamber (lines correspond to traces in Fig. 1(b)). As the backscattered power increases with the gas pressure, the movement of the gas pressure profile is observed. Fig. 1(e) shows measurements of the reverse process, whereby the pressurised NANF was removed from the chamber and allowed to vent.

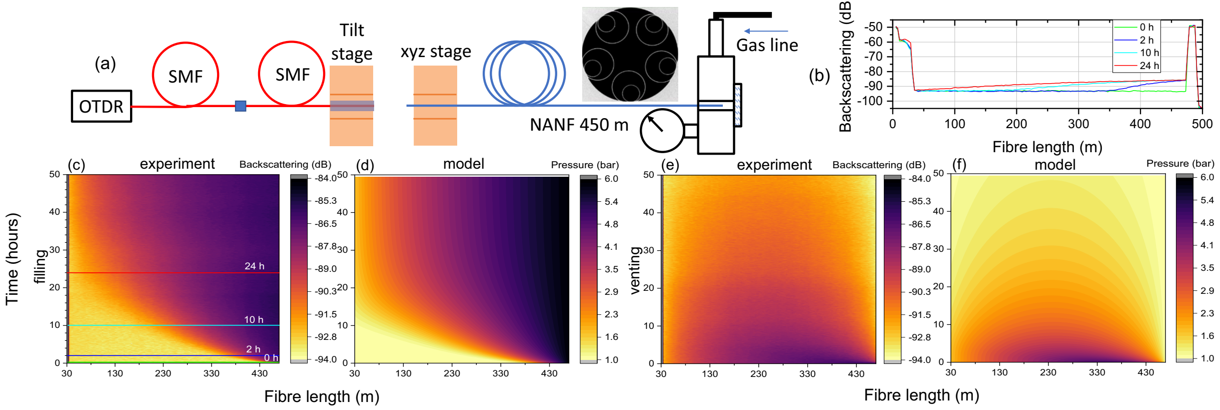

Fig. 1 (a) Experimental setup. (b) OTDR traces throughout NANF filling. Backscattering as the NANF was filled (c) and vented (e). Modelled gas pressure distribution inside a capillary representing the NANF's core for filling (d) and venting (f).

We compare our experimental results to a simplified circular capillary (with a diameter equal to that of the NANF's core) gas flow model [5]. The simulated evolution of the pressure distribution inside such a capillary, using our experimental conditions, is shown in Fig.1(d) and (f) for filling and venting respectively. Overall, the model fits the experiment well, though for both filling and venting, the experimental results are slightly slower than the simulations. This is attributed to the impact of the small gaps between the NANF cladding elements and work is ongoing to clarify whether a generalised scaling factor can be used to increase the application of this gas flow model to NANFs. This work therefore validates this experimental approach for distributed measurements of gas flow dynamics within HCFs and opens up means to measure pressure distributions in HCFs, to further inform HCF fabrication, characterisation and applications.

References

[1] S. Rikimi et al., "Internal Gas Composition and Pressure in As-drawn Hollow Core Optical Fibers," in J. Light. Technol., **40**, 4776 (2022)
[2] T. W. Kelly et al., "Gas-induced differential refractive index enhanced guidance in hollow-core optical fibers", Optica, **8**, 916 (2021).
[3] H. Sakr et al., "Hollow Core NANFs with Five Nested Tubes and Record Low Loss at 850, 1060, 1300 and 1625nm", in OFC 2021 F3A.4.
[4] R. Slavík et al., "Optical time domain backscattering of antiresonant hollow core fibers", Opt. Express, **30**, 31310 (2022).
[5] J. Henningsen and J. Hald, "Dynamics of gas flow in hollow-core photonic bandgap fibers", Appl. Opt., **47**, 2790 (2008).