Spatially Resolved Pressure Measurement of Antiresonant Hollow-Core Fibres Using Nonlinear Optics

Mitchell Gerrard[1], Seyed Mohammad Abokhamis Mousavi[1], Radan Slavík[1], Peter Horak[1]

1. Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

Hollow-core optical fibres (HCFs) guide light in an air-filled hole and exhibit lower loss, lower optical nonlinearity, and lower latency than solid fibres. Pressurising the fibre core with bespoke gases allows for tunability of chromatic dispersion and nonlinearity. Likewise, evacuation of the HCF core can further reduce nonlinearity and phase noise for high power transmission and ultra-stable interferometry, respectively. For these applications, methods to measure the pressure inside the HCF are needed; for example, studies using OTDR have achieved 1.5 m spatial resolution [1]. Here, we numerically investigate pressure measurements via four-wave mixing (FWM) and cross-phase modulation (XPM).

For FWM-based pressure measurements, a strong pump and weak signal pulse are launched into the fibre. As they travel with different group velocities, they overlap for a certain interaction length where a third idler wave is generated depending on phase mismatch and optical nonlinearity. Chromatic dispersion can be measured or simulated, thus the idler power is a measure of the nonlinearity and thus of gas pressure. Changing the time delay between the launched pump and signal pulses changes where they interact in the fibre, providing spatial resolution.

XPM-based pressure measurement also uses a pump and signal pulse at different frequencies with tunable delay at the fibre input. Where they spatially overlap along the fibre, the weak signal pulse experiences an additional phase shift induced by the Kerr effect of the strong pump pulse. This phase shift, depending again on pulse walk-off length and gas nonlinearity, can then be measured by an interferometric setup at the fibre output and provides a measurement of the gas pressure at the pulse interaction position.

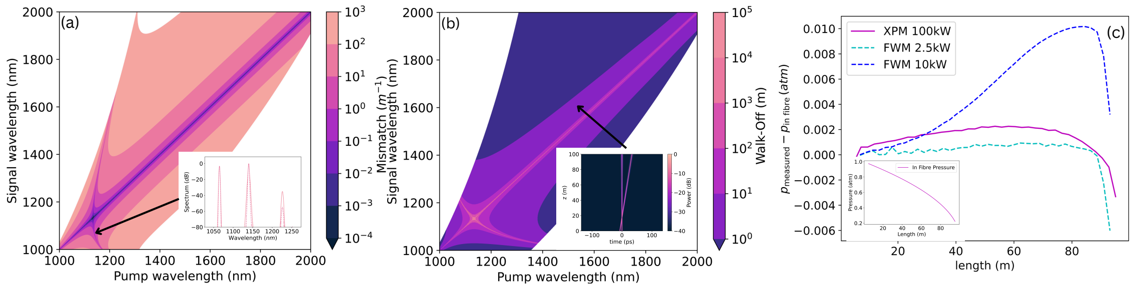

Fig. 1 (a) Phase mismatch between pump, signal, and idler for FWM in chosen fibre. Inset: FWM output spectra at 1 atm (solid) and 0.1 atm (dashed). (b) Corresponding walk-off length between pump and signal. Inset: NLSE simulation of walk-off. (c) Deviation of predicted gas pressure in HCF core from true pressure (shown in inset). 1 ps pulses. Legend gives peak power.

We simulate these two schemes using the nonlinear Schrödinger equation (NLSE). Fig. 1(a) shows the phase mismatch between pump, signal and idler, calculated for a tubular antiresonant fibre with 10.25 μm core radius and seven capillaries of 446 nm glass thickness. Efficient FWM is restricted to the dark areas (low mismatch), thus severely limiting the choice of wavelengths. Fig. 1(b) shows the corresponding walk-off length, which controls the region of signal and pump overlap and thus the generated idler power but also the achievable spatial resolution of the pressure measurement. By trading off idler power we find 3-7 m resolution with reasonable conversion; here we use pump and signal wavelengths of 1140 nm and 1065 nm. Note, however, that the idler power scales with the square of the pump power. The XPM approach, on the other hand, does not depend on phase matching, and thus experimentally more convenient wavelengths can be chosen; here we use 1550 nm and 1600 nm giving a resolution of 2 m. Moreover, the XPM-induced phase shift of the signal scales linearly with pump power.

Fig. 1(c) shows the pressure profile of a 100 m long fibre (inset) and the accuracy of the numerically simulated FWM and XPM based measurement approaches. We see that the XPM approach at low pump power gives the most accurate results. The experimental challenge here is to separate the weak idler power from the strong transmitted pump signal. At high pump powers, the idler power increases quadratically, thus making detection easier, but nonlinear pulse distortion leads to deviations in the estimated pressure in the fibre. The XPM-based approach requires high pump powers because of the small nonlinearity of gas and a more complex interferometric setup but is more robust to fibre fabrication and environmental conditions as it does not rely on phase matching.

In conclusion, both FWM and XPM based schemes seem appropriate for spatially resolved core pressure measurements along HCFs, with XPM perhaps the more straightforward to perform experimentally.

References

[1] X. Wei, B. Shi, D. J. Richardson, F. Poletti, and R. Slavík, “Distributed characterization of low-loss hollow core fibers using EDFA-assisted low-cost OTDR instrument,” 2023 Optical Fiber Communications Conference (OFC), paper W1C.4 (2023).