Real time gas detection using optical fibre the width of a human hair

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Abstract

Many applications can benefit from highly sensitive, fast response gas detection including atmospheric mapping and combustion diagnostics. Optical fibres, only 200 µm (0.02 cm) across, can be used to make a compact gas detector, where the detection is carried out via a technique known as spectroscopy using the light propagates which down the fibre. To get a quick detection, small holes, referred to as "microchannels", can be fabricated along the fibre length so the gas fills the entire fibre length in one go.

1. Optical Fibre

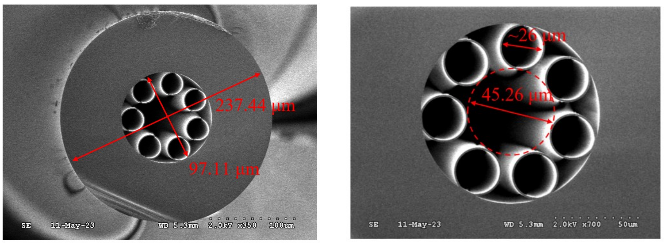


Figure 1: Scanning electron microscope images to show the dimensions of the hollow-core fibre.

- Optical fibre is essentially a long waveguide which propagates light down its length. This work uses a special type of fibre known as hollow-core fibre.
- The circular capillaries in Fig. 1 which surround the central hollow region confine the light to the core.

3. Gas Detection

- The machined fibre is then placed inside compact tubing (Fig. 5) which can be filled with the gas of choice. The gas will then defuse into the entire fibre length through the microchannels and interact with the light coming from a connected laser.

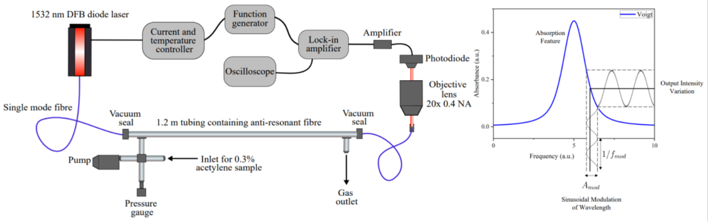


Figure 5: Experimental setup used for direct absorption and WMS with the machined 1 m fibre.

- The gas is detected via spectroscopy when light from a laser is absorbed by the gas as the electrons in the gas molecule are excited. Plotting this absorption against wavelength gives peaks of absorption (Fig. 6(a)) at specific wavelengths, and specific to the gas species. The absorption peak is higher for a greater concentration of gas. The gas used in this work is a 0.3% sample of acetylene.
- To improve the result, the laser can be modulated at a higher frequency (Fig. 5) for the measurement, where excess laser noise is less, and then demodulated afterwards to get a harmonic proportional to the absorption (Fig. 6(b)). This is known as wavelength modulation spectroscopy (WMS) and gives a higher sensitivity.

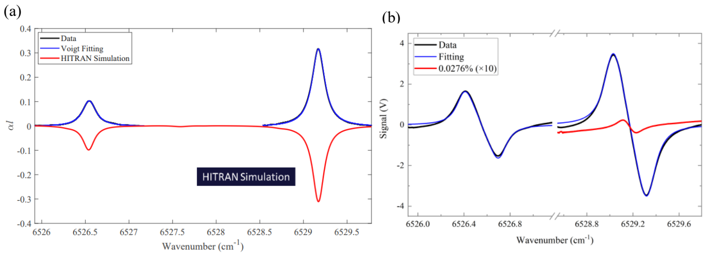


Figure 6: Detected absorption (a) direct absorption fitted with a Voigt profile (b) 1st harmonic from wavelength modulation spectroscopy .

Conclusion

Periodic microchannels have been fabricated down the length of a 1 m hollow-core fibre with a width of only 200 µm for detection of 0.3% acetylene. The system has, simultaneously, a fast response time of < 5 s with high sensitivity (minimum detection limit of 380 ppb). Further work could push the technology to be even closer to real time by reducing microchannel separation.

2. Fibre Micro-Machining

- To fill these fibres with the gas sample in a short space of time, small holes, microchannels, can be fabricated periodically down the length of the fibre where there is a gap between the capillaries. The microchannels are just 5 µm (0.0005 cm) wide.
- The smooth microchannels are fabricated using a high power laser which results in only a small increase in the loss of light from the fibre.

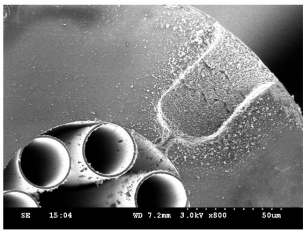


Figure 2: Cross-sectional image of the ablated cladding and microchannel.

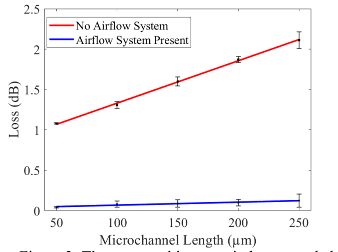


Figure 3: The measured increase in loss recorded for increasing, 5 µm wide, microchannel lengths.

- 20 microchannels (dimensions, 5 x 50 µm) are fabricated at a 5cm separation along a 1 m sample of fibre, as shown in Fig. 4.

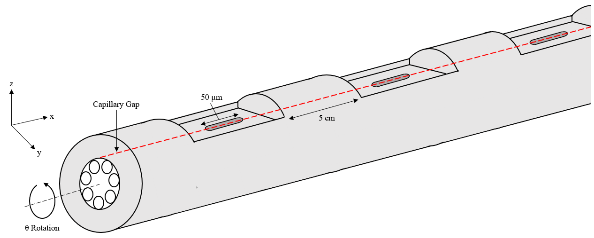
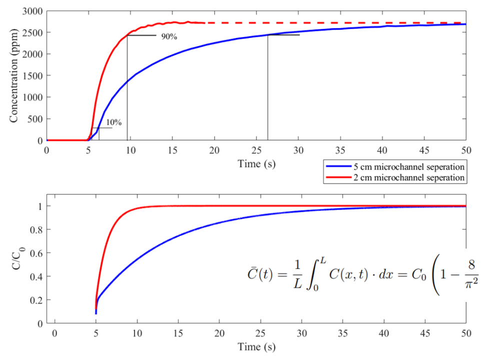


Figure 4: The microchannels are fabricated periodically down the length of a fibre every 5 cm.

4. Response Results



$$\bar{C}(t) = \frac{1}{L}\int_0^L C(x,t)\cdot dx = C_0\left(1 - \frac{8}{\pi^2}\cdot\sum_{j=1,3,5}^{\infty}\frac{1}{j^2}\cdot\exp\left[-\left(\frac{j\pi}{l}\right)^2 D\cdot t\right]\right)$$

5 cm separation: 22 s
2 cm separation: 4.2 s

Figure 7: The recorded increase in the concentration of acetylene for fibres with different microchannel separations. The gas sample is introduced to the fibre tubing at 5 s.

- The time response of the fibres is seen in Fig. 8 by recording the increase in the amplitude of the absorption after the gas is allowed to enter the tubing containing the fibre.

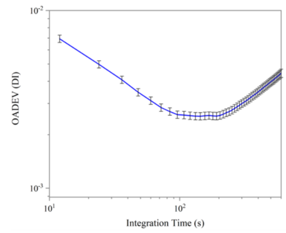


Figure 8: Overlapping Allan deviation analysis.

α_{min} = 3.96 x 10^{-7} cm^{-1} / m of fibre

380 ppb / m of fibre

- An Allan Deviation analysis in Fig. 9 shows the long term stability of the system as it measures the variance of the signal with time.