Evaporation of fluids in suspended-core fibres

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Abstract: A segment of a suspended-core microstructured fibre was dipped in a droplet of acetone and the evaporation dynamics of remaining acetone inside the cavity were simultaneously analysed with an optical microscope and an optical spectrum analyser. When the fibre is immersed it suffers a 14 dB signal drop. Different menisci form in each cladding cavity, with different evaporation times and rates. The signal restores its initial state not when the evaporation process is complete but after the collapse of a dominant meniscus.

Keywords: optical fibre sensors, suspended-core fibres, fluid evaporation monitoring

1. Introduction

Suspended-core optical fibres are characterized by their nanowire-like small diameter cores held by thin struts in the middle of large air holes[1]. By reducing the core size, an increasing fraction of core guided modes protrude into the air holes. Light can then strongly interact with fluids that are inserted into these holes without the characteristic frailty of thin nanowires. Although hollow-core photonic bandgap fibres also have a large interaction area with the air holes, the ease of fabrication of suspended-core fibres gives them a competitive advantage when planning for industrial applications[2].

The interaction between the evanescent field and fluids inserted into microstructured fibre holes has been the object of extensive study for sensing purposes. Suspended-core fibres have been used to measure physical parameters[3], for Raman and fluorescence spectroscopy[1,3], and in biological and chemical sensing. In particular, measurements of liquids have been performed either by effective refractive index changes in interferometric setups or by absorption spectrum analysis[4].

Recently, Preter et al. introduced a new technique in microstructured fibres for liquid sensing[5]. Using in-line micro-cavities etched in single-mode fibres, the authors proposed the monitoring of the evaporation dynamics of volatile organic compounds as a means to identify them. They tracked the evaporation of ethanol, hexane, acetone, and a mixture of ethanol and hexane, observing clear distinctions in light loss dynamics, which effectively resulted in a volatile organic compound sensor.

In this work, the concepts used in microcavities are applied to a suspended-core fibre tip. The time-dependent spectral response of a suspended-core fibre is coarsely monitored when its cavities are filled with acetone. The phenomenon was observed simultaneously using an optical microscope. We chose to analyse the full spectral response and not be limited to a narrow wavelength region in order to analyse possible formation of Fabri-Pérot cavities and spectral phase shifts during the evaporation process.

2. Setup and Procedure

Fig. 1 (a) represents schematically the experimental setup. A suspended-core fibre section with a (1.38 ± 0.02) mm length was fusion spliced to a standard single-mode fibre. An asymmetric four-bridge silica fibre with a double-Y-shaped suspended-core was used. The cross-section of the microstructured fibre can be seen in Fig. 1 (b). The outer diameter is 130 µm while the diameter of the air-hole cladding is 65 µm. The core (Fig. 1 (c)) is approximately rectangular with a length of 6.5 µm and a width of 1.5 µm.

The sensor was studied when a droplet with a few tens of microliters of acetone was dispensed with a syringe on the open end of the suspended-core fibre on a microscope slide. To perform the interrogation, the single-mode fibre was connected to an optical circulator. Light was introduced from a 100 nm-wide optical source centred at 1550 nm and the reflected signal was interrogated using an Optical Spectrum Analyser (OSA) with a maximum resolution of 0.01 nm.

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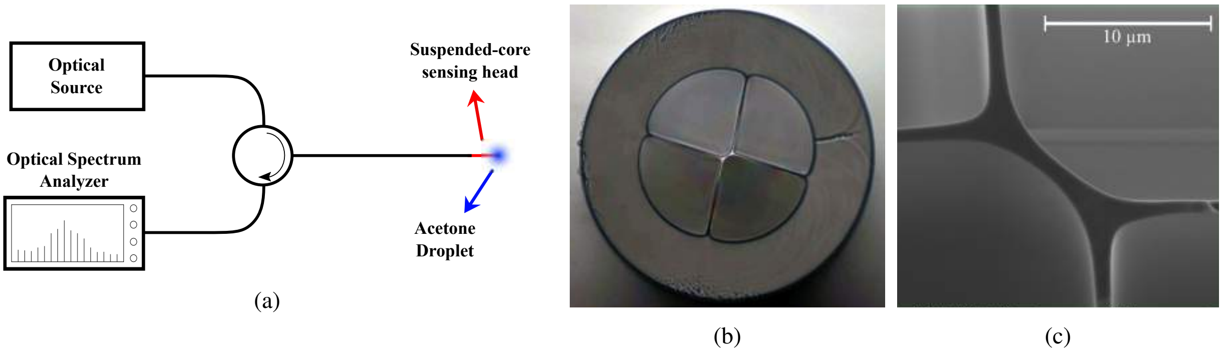

Figure 1. (a) Diagram of the experimental setup. (b) Suspended-core fibre cross-section. (c) SEM image of the core region.

3. Results

Figure 2 contains a series of pictures that show the evolution of acetone evaporation from the sensing head. When acetone is dispensed on a clean sensing head the air-holes are filled by capillarity forces and excess liquid that surrounds the fibre tip rapidly evaporates. As soon as the acetone that covers the tip evaporates, four menisci form (a) inside each individual cavity. For clarity, arrows indicate the position of each meniscus. Each hole has a different evaporation rate and some seconds after the formation of all menisci, the differences in position between all four menisci are clear, as seen in (d). When acetone in an individual cavity evaporates completely, its meniscus collapses. Due to the different evaporation rates, this happens sequentially in each cavity.

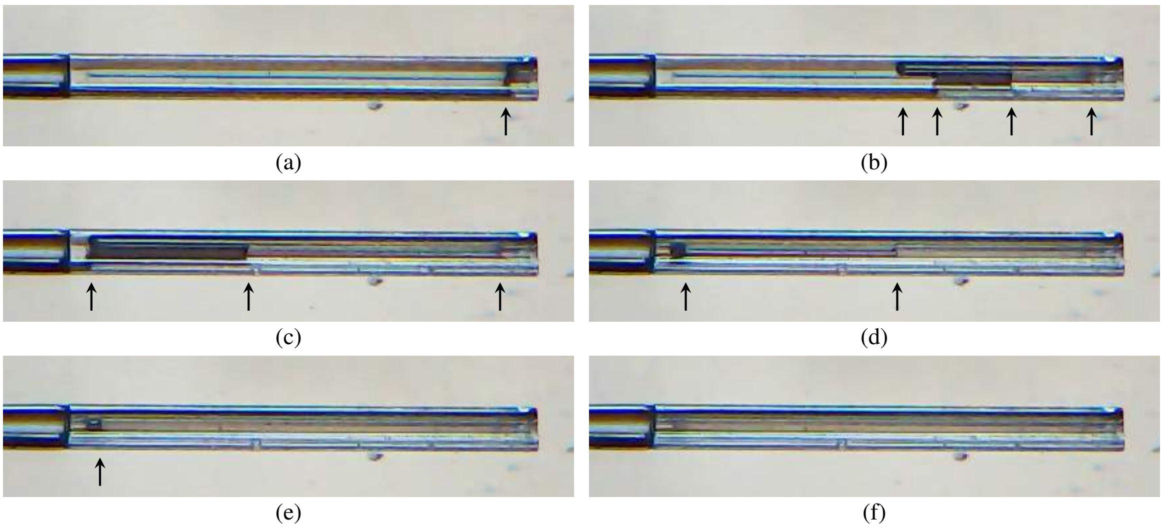

Figure 2. Evolution of acetone evaporation from the sensing head since the formation of menisci (a) until the evaporation process is over (f). Arrows indicate the positions of menisci.

After repeating the experiment one notices that the evaporation dynamics depend on the way acetone fills the cavities, for this particular configuration. Air bubbles may form inside the holes causing differences in evaporation rates and total duration and decreasing reproducibility. The sensing head used shows an average evaporation time of ~ 45 s.

During the study of evaporation dynamics, the sensing head was continuously interrogated using an OSA. The OSA's slow time response resulted in a small resolution of ±4 s. This allowed for a coarse spectral analysis of the phenomenon. The data acquired is plotted in Fig. 3. A two-wave interferometer spectrum can be seen, with a period of 0.6 nm, practically constant throughout the whole process, and an amplitude of 0.3 dB. Figure (a) shows the sensor's spectrum before acetone was dispensed. When the sensor is immersed in acetone (b) the reflected signal intensity drops 14 dB due to the higher refractive index of acetone (~ 1.36) in comparison with air and the consequent reflectivity decrease on the fibre tip interface. When the menisci form, a 3 dB amplitude increase is observed (c). As acetone inside the cavities evaporates this amplitude decreases (d). The spectrum returns to its initial form after the first meniscus collapse. From then until the end of the evaporation process, the spectrum retains the same average signal value, suffering only a spectral phase shift (f).

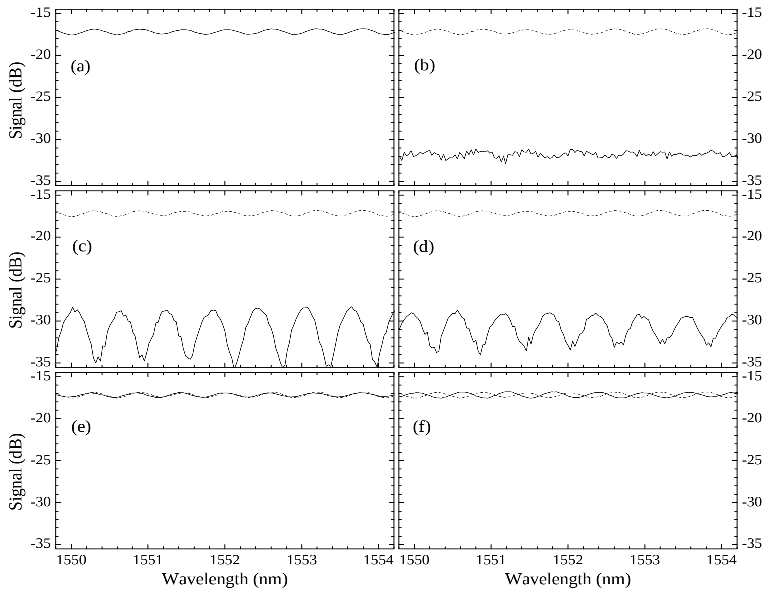

Figure 3. Spectral evolution measured with reference to the optical source since before dispensing acetone (a) until the evaporation process is over (f). For ease of comparison, data from (a) is repeatedly plotted as a dashed line.

4. Discussion and Conclusion

A four-bridge suspended-core microstructured fibre tip was immersed in a droplet of acetone and the evaporation dynamics were simultaneously analysed with an optical microscope and an optical spectrum analyser. The formation of four different menisci in each cladding cavity was observed, each with different evaporation times and rates due to acetone filling occurring in an inhomogeneous manner. One would expect the spectrum to return to its initial state only after the collapse of the four menisci. However, this happened after the collapse of the first meniscus (Fig. 2 (e) and 3 (e)), suggesting that there is a dominant cavity and that not all of them have a similar contribution. This effect could be related either with the core's asymmetry or the setup's horizontal geometry and it will be pursued in future studies.

With decreasing length one expects fluids to fill the cavities in a more uniformly. Thus, although requiring faster interrogation due to shorter evaporation times, experimental repeatability should increase for smaller sensor lengths. Also, a vertical dipping setup should provide higher uniformity in both filling and evaporation processes. Future developments will include time-domain analysis and study of other compounds in order to test the sensor's capacity to differentiate between compounds. With this we expect to obtain a greater understanding of the sensor's global behaviour so as to allow the design of sensing solutions for low-volume fast volatile organic compound recognition, useful for industrial or environmental process monitoring.

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