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Abstract. A multimodal interferometer based on a new microstructured fiber tip is proposed for detection of the evaporation process of acetone. The new geometry consists of a capillary tube in which an offset Ge-doped core is fused and spliced at the end of a single-mode fiber. The fiber tip sensor structure was immersed in liquid acetone and the evaporation process of acetone was monitored in real time. Due to the refractive index variation of the external medium with increasing temperature, a short detection time of ∼1 s was achieved. [DOI: 10.1117/1.OE.53.8.080501]

Keywords: multimodal interferometer; optical fiber sensors; evaporation of acetone; microstructured fibers.

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1 Introduction

In the past few years, several studies have been dedicated to the interaction of light with fluids, namely, for refractive index measurement. Optical fiber-based configurations have been widely used to perform this task. The use of fiber taper as the sensing element gained particular interest in this area of research due to the evanescent field interaction with the surrounding medium.[1] However, parameter measurement solely depends on light signal intensity variation, which is a drawback for the development of high-performance sensors. With the appearance of microstructured optical fibers (MOF), it was possible to overcome this limitation. In particular, liquid sensing has been performed either by effective refractive index changes in interferometric setups or by absorption spectrum analysis.[2]

The interaction between the evanescent field and fluids inserted into MOF holes has been the object of extensive research for sensing purposes. Several configurations have been studied, namely, with hollow-core photonic crystal fibers (PCFs),[3] suspended-core PCFs,[4] and others.[5] Recently, a new technique was introduced in MOFs by etching in-line microcavities in single-mode fibres.[6] The fiber device was proposed for monitoring the evaporation dynamics of volatile organic compounds and successfully identified them.

In this work, a multimodal interferometer based on an MOF tip is proposed for the detection of the evaporation process of acetone. The time-dependent spectral response of said sensor was monitored when it was immersed in liquid acetone and submitted to an increasing temperature until its boiling point. Such a sensor has shown to be sensitive to external refractive index variation caused by the evaporation process of acetone.

2 Experiment

With this approach, the sensing head was interrogated in reflection by means of a distributed feedback laser with a central wavelength of 1570 nm and 1 mW, an optical circulator to analyze the sensing head in reflection, and a photodetector followed by signal processing using LabView™. The experimental setup and detail of the sensing fiber used in the experiment is shown in Fig. 1.

The special optical fiber is made of a pure silica tube with a lateral germanium-doped silica core. The tube has an outer diameter of 180 μm and a thickness of 50 μm, which allow the fiber to be spliced with a standard optical fiber while keeping a free access for a liquid into the tube. The core is 3.9 μm in diameter, ensuring single-mode operation and evanescence of the propagated electromagnetic (EM) field into the surrounding medium due to the small dimension of the core. For the fabrication of the fiber, a two-step drawing process (structured intermediate cane and final fiber) has been used to provide sufficient control of the geometry. The Ge-doped silica rod was simply glued at high temperature into a suitable silica tube during the first step. This structure also exhibits a parabolic index profile in order to provide single-mode operation. During the fabrication process, we have paid a great deal of attention to the drawing parameters in order to minimize the contact surface between the Ge-doped silica core and the external tube. Indeed, as the core diameter has been minimized to improve the interaction of a propagated EM field with the surrounding material (that is to say, maximizing the evanescence of the field in the liquid), the EM field can easily spread into the surrounding silica tube, which is detrimental to its expected interaction with liquid. Numerical analysis of the proposed sensor configuration was performed for two surrounding mediums, namely, air and acetone, as is shown in Fig. 2. For the operation wavelength at 1550 nm, one leaky core mode spreads toward the silica tube and not into the air [Fig. 2(a)] and two guided modes leak toward the silica tube and not into the acetone [Fig. 2(b)].

The microscope image of the microstructured fiber used in the experiment is depicted in Fig. 3. The sensing head consists of a small section (L) of the MOF tube, ca. 10 mm in length, spliced at the end of a single-mode fiber (SMF-28), thus forming a fiber tip device. The fabrication process consisted of applying a splice offset between the SMF and the

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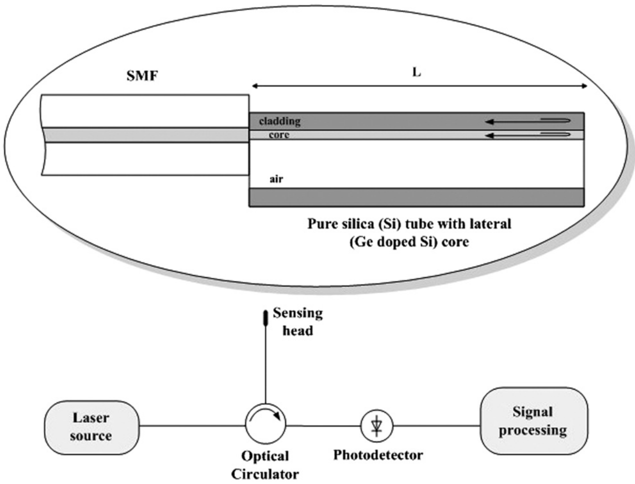

Fig. 1 Experimental setup with the detail of the proposed sensing head.

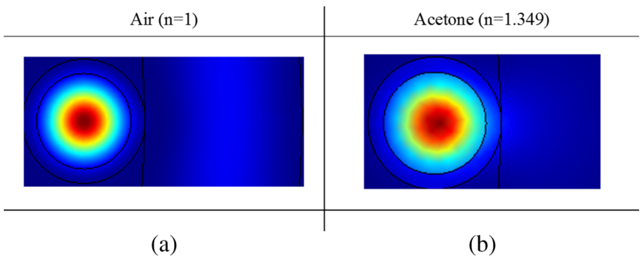

Fig. 2 Numerical analysis of the proposed sensor configuration for the surrounding mediums of (a) air and (b) acetone.

silica tube in order to align both fiber cores. To guarantee a good fusion between the two fibers, a fusion splicing machine was used in manual operation with an electric arc current of 70 mA and duration time of 400 ms. Assuming that both fiber cores are aligned, the splice loss α between both fibers can be estimated by[7]

$$\alpha = -20 \log\left(\frac{2\omega_1\omega_2}{\omega_1^2 + \omega_2^2}\right), \tag{1}$$

where ω_1 and ω_2 are the mode-field diameters of the SMF and microstructured fiber, respectively. In this case, the estimated splice loss is ~2.2 dB.

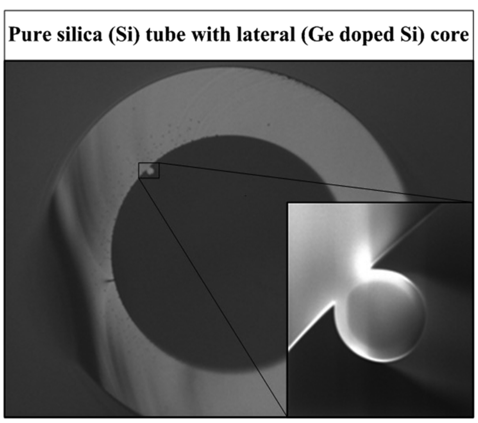

Fig. 3 Microscope image of the microstructured fiber used in the experiment.

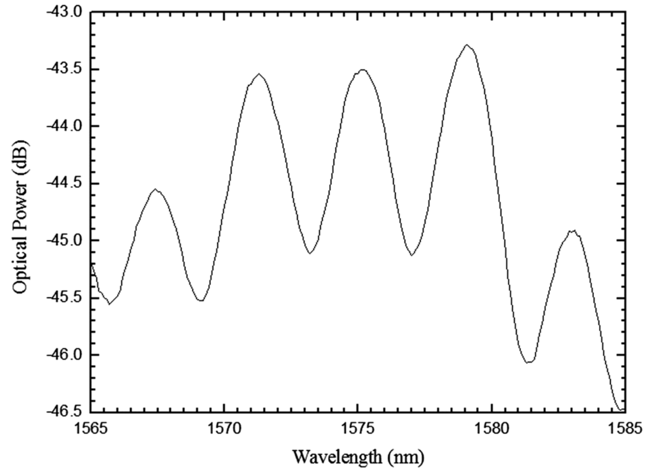

Fig. 4 Optical spectrum of the proposed sensing head.

Figure 4 illustrates the spectral response obtained with the proposed sensor structure when it is illuminated by a broadband source. The wavelength separation between two consecutive peaks is ~3.9 nm. The refractive index difference obtained is 3×10^{-2}, which corresponds to multimodal interference between the core and the cladding of the silica tube.

Due to the small core diameter of the silica tube MOF (approximately half that of the SMF), light that comes from the SMF is launched into the core of the MOF, originating a multimodal interferometer. The principle of operation is the interference between the modes created by MOF design, which are backreflected at the end of such fiber. The light modes interfere in the splice region between the MOF and the SMF creating an interference pattern. The optical path is obtained through the refractive index difference between modes.

To perform the experiment, the MOF-based fiber tip was immersed in liquid acetone and submitted to increasing temperature until acetone reached its boiling point (~56°C). In this case, the pattern fringes of the multimodal interferometer will be sensitive to the external refractive index variation

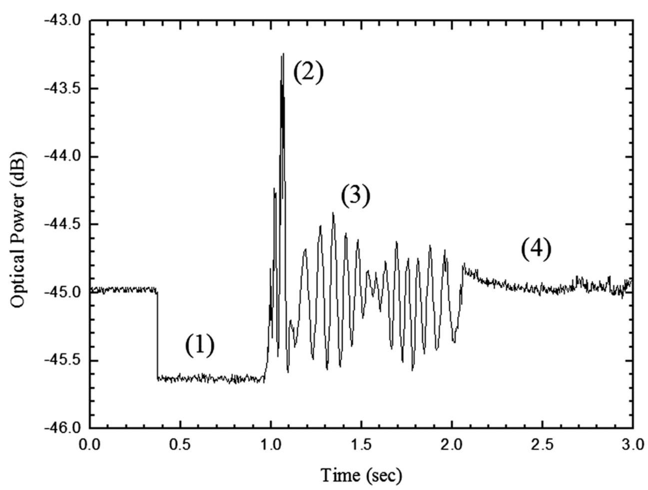

Fig. 5 Temporal evolution of the sensing head during the process of acetone evaporation: (1) immersed, (2) endothermic reaction, (3) phase change, and (4) in air.

caused by the evaporation process of acetone. The result is depicted in Fig. 5.

This result arises from monitoring the sensing head behavior at a single wavelength (1570 nm), when it is submitted to the increasing temperature of liquid acetone until its evaporation. The spectral evolution of the sensing head is then characterized by four stages: (1) the sensing head immersed in liquid acetone, at room temperature—the silica tube is filled with acetone and, due to its refractive index (1.349 at 1550 nm and room temperature[8]), the intensity of the channeled spectrum decreases to ∼0.65 dB (the visibility decreases with the increasing refractive index of the surrounding medium[9]) and is maintained constant along the time; (2) acetone evaporation once reaches its boiling point, at ∼56°C;[10] (3) phase change of the channeled spectrum caused by gradual evaporation of the acetone inside the silica tube and also due to temperature variation caused by the endothermic reaction; (4) recovery of fringe visibility due to total evaporation of the acetone inside the silica tube.

A beat phenomenon is also visible, which is originated by multimodal interference, but is not observable in the optical spectrum presented in Fig. 4. The proposed sensor detected the evaporation of acetone in ∼1 s (from endothermic reaction to signal visibility recovery).

3 Conclusion

A multimodal interferometer was developed for the detection of acetone evaporation. The proposed sensor combines the simplicity of the fiber tip configuration with the high sensitivity of the interferometric behavior. The sensor also presented excellent reproducibility within a short detection time (∼1 s). In practical sensing applications, the proposed fiber tip sensor may provide *in situ* single-point measurement and low-volume fast volatile organic compound recognition, which is useful for industrial or environmental process monitoring. Future developments may include the use of fast interrogation schemes in order to obtain a higher time resolution of the evaporation process.

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