Optical Fibre Fabry-Pérot Sensor Stability at High Temperatures

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ABSTRACT

In this paper we present long-term stability results for a Fabry-Pérot optical fibre sensor in high temperatures environments. We introduce an intrinsic Fabry-Pérot type of sensor, which its sensing element is made with an undoped pure fused silica cavity. Furthermore, we will present results detailing dopant diffusion from core to cladding of standard optical fibres demonstrating their inherent unsuitability for high temperature environments. Finally, we display the manufacturing technique required to produce this sensor and we present results of 33 days long stability tests conducted at elevated temperatures of more than 900^{o}C.

Keywords: Fabry-Pérot cavity, fiber optic sensor, pure fused silica, temperature, PCF

1. INTRODUCTION

Over the past decades, optical fibre sensing has gained a huge interest in numerous industrial high temperature applications. One of the key applications for which optical fibre sensing has been found to be very promising is aerospace components e.g. aircraft turbines, spacecraft components and airplane wings [1]. Within these components a range of parameters such as chemical corrosion, temperature, pressure, humidity and strain can be detected and measured with accuracy through the use of optical fibre sensors [2]. Some of the advantages which make optical fibre sensors unique include: submicron size, robustness, electromagnetic immunity, high sensitivity and their potential for embedding in metallic components [3] are important considerations in this field. An equally important element, affecting the stability and the physical structure of the sensor, is the dopant diffusion that has been found to arise at high temperatures [4]. Standard telecommunication fibre (SMF28 ultra), which has been extensively used in sensing applications, is doped with a low percentage of germanium. Under high temperatures this germanium diffuses into the cladding region, altering the refractive index of both the core and the cladding, the refractive index contrast between them, and affecting the viscosity of the optical fibre [5]. As a result, the refractive index change influences the phase stability of our Fabry-Pérot sensors. In our previous works, we presented preliminary results (recorded over 17 days) of a pure fused silica sensor, its stability behaviour at high temperatures [6] and measurements of the dopant diffusion of the sensor from the core to the cladding [7]. After examining optical fibre sensors at high temperatures over long periods, we concluded that the diffusion is a fact which plays an important role in the stabilization (or de-stabilization) of the optical fibre sensor, especially in harsh environments. In this work, we extend the stability tests of an intrinsic pure fused silica Fabry-Pérot sensor, for a period of 33 days in a temperature range from 900 ^{0}C to 1050 ^{0}C. Moreover, germanium core diffusion results on two different points along a sensor are demonstrated, for an interval of 90 days, acquired by Scanning Electron Microscopy coupled with Energy Dispersive X-ray (SEM/EDX) spectroscopy.

2. EXPERIMENTAL DISCUSSION

Initially, the sensor used in our experiments was formed by a long length of SMF28 ultra optical fibre, which was cleaved and coated with a thin film of chromium. The thin chromium film works as a low finesse reflective mirror. Then, the chromium coated SMF28 fibre was spliced to a single mode PCF (ESM-12B) optical fibre. Both were cleaned in an ultrasonic bath and cleaved before splicing. We initially align the SMF28 ultra fibre with the PCF fibre with a Vytran FFS-2000 fusion splicing workstation. After the alignment of both cores we choose suitable parameters (e.g. splice intensity = 18.5W) for optimized splicing. A strong and well aligned splice eliminates signal loss thus maintaining the fringe visibility of the interferometric signal. While the tungsten filament of the Vytran splicer fuses the two fibres together, the fusion collapses the air holes of PCF fibre.

The outcome is that a short PCF length becomes a pure fused silica rod, which can be cleaved at a specific length in order to generate a pure fused silica Fabry-Pérot sensor. Following this process, the sensor is ready to be introduced in a furnace (Nabertherm RD 30/200/11) for heating. The cavity length of the pure fused silica sensor is 63µm (**Figure 1)** and both fibres share the same diameter of 125µm. As can be seen in **Figure 1** the thin chromium layer works as a reflective mirror, while the end of the sensor tip works as a second reflective mirror (Fresnel reflection ~3.6%). The interference signal which is generated by these two reflective mirrors has a sinusoidal form, shown in **Figure 2**. The fringe visibility of the spectrum is calculated as V= 1.

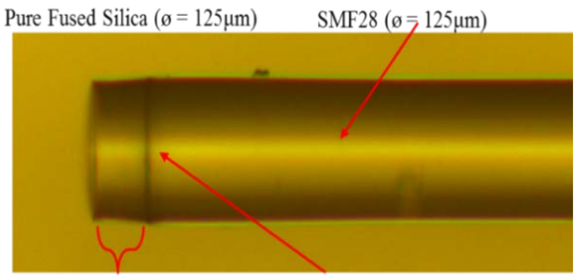

Figure 1. SEM photo of the pure fused silica sensor, we used in our experiments.

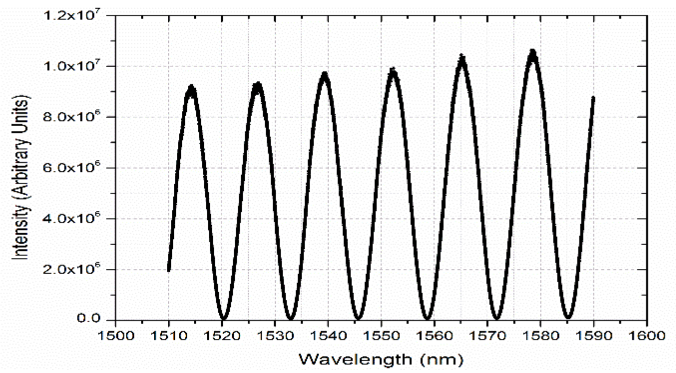

Figure 2. Interference signal of a 63µm cavity F-P sensor.

In our experiments, the data reduction and extraction of the sensor temperature involves multiple stages of data manipulation. The fundamental frequency, after applying a Fast Fourier Transform on the spectrum of the sensor (**Figure 2**), is used as a seed for fitting a sinusoidal equation. The fundamental frequency of the spectrum and the phase of the sinusoidal fit were extracted from this data while the furnace temperatures varied and an independent measurement of temperature from the thermocouple (N-type thermocouple) was recorded at the same time. We have found that the sensor's sensitivity at 200^0C is 5.83mrad/^{0}C, while at 1000^0C it rises to 8.84mrad/^{0}C, as shown in **Figure 3**, which is a result of the second order dependency of the thermo-optic coefficient [8, 9].

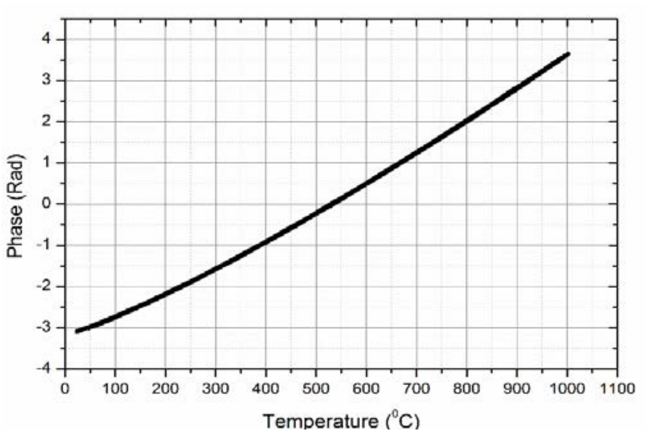

Figure 2. Phase response (Radians) with respect to temperature (^{0}C), while cycling down from 1000^0C to room temperature.

Figure 4 illustrates the phase behaviour of the above mentioned sensor, for an extended period of time (33 days). On the left axis we display the phase response in radians while on the right axis we place the corresponding temperature recorded separately with an N-type thermocouple. Initially the sensor was subjected to a series of annealing cycles, from room temperature to 1000^0C (one cycle is shown in **Figure 3**). Through the annealing cycles the optical fibre is released from thermal stress, which makes the sensor suitable for long term operation at a specific high temperature. The stability test started at 900^0C and every 4 days the temperature was been increased or decreased, depending on the progress of the experiment, by a step of 50^0C. At the upper left corner of **Figure 4**, the temperature of 28^0C corresponds to the calculated temperature of the sensor for 0.5 radians, through its sensitivity at 1000^0C. From this calculated temperature we can roughly estimate the temperature drift of the sensor, by recognizing its drift in radians per degrees Celsius.

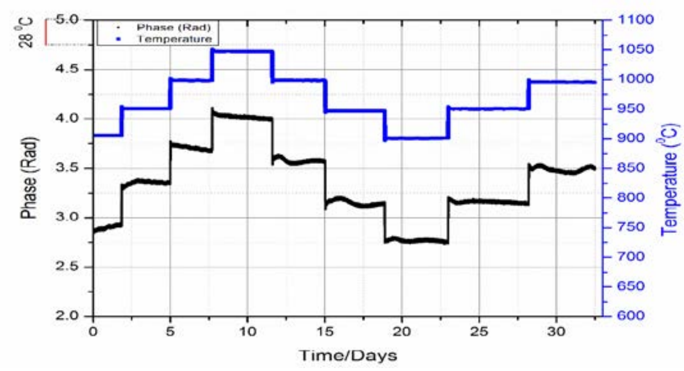

Figure 3. Long term (33 days) phase response testing of the pure fused silica Fabry-Pérot sensor.

A clearer illustration of the sensor's phase response, at temperatures of 1000^0C and 950^0C, is demonstrated in **Figure 5** and **Figure 6**, respectively. In both figures the drift of the sensor is made clear in the graph. At 1000^0C the sensor's temperature drift (left axis), after approximately 3 days, is roughly 7^0C while the thermocouple's temperature drift (right axis) is less than 1^0C. Similarly, for a period of 4 days at 950^0C sensor's temperature drift is estimated to be roughly 5^0C, when thermocouple's drift is infinitesimal. Considering that our sensor is still a work in progress, we cannot make strong claims about achieving stability for more than a few days as the modulations during the stability test are noticeable in both figures.

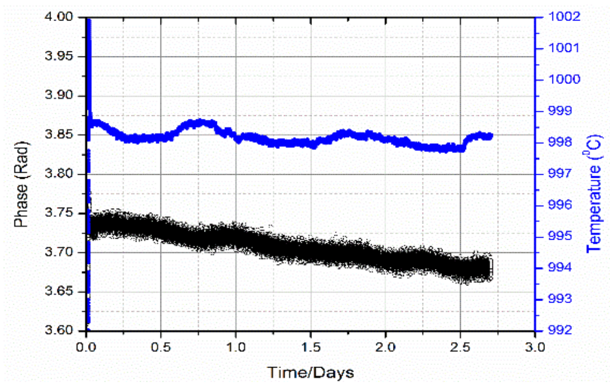

Figure 4. Phase response at 1000^0C during the first stability cycle.

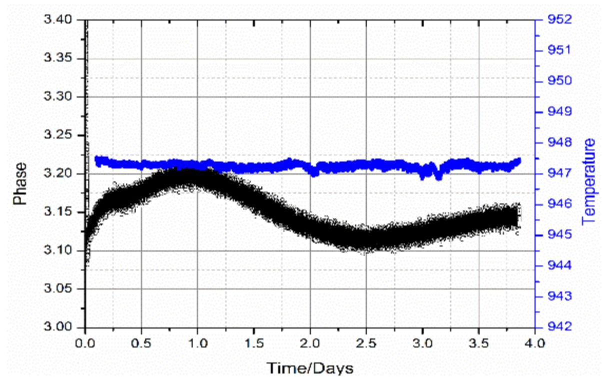

Figure 5. Phase response at 950^0C during the second stability cycle

We attribute these modulations to a second order cavity which is created from the germanium diffusion from the core to the cladding. Despite the pure fused silica's cavity, which creates the main interference signal (**Figure 2**), the rest of our sensor consists of a germanium doped smf28 fibre. The length of the fibre which sits in the furnace is roughly 17cm, thus the rest of the fibre in which the fundamental signal is travelling, is heated. Hence, the dopant diffusion takes place along the whole fibre which sits in the furnace, causing an adiabatic tapering to the core of the fibre and leading subsequently to a monotonic increase of the core radius [10]. In this context, the new core diameter can support a second order mode travelling in the core alongside the first order mode. There is a small percentage of energy exchange between the first and second mode, activating the second order mode and creating the propagation of another cavity's signal. In the context of this dopant diffusion and the expected core radius increase, we conducted a line scan EDX measurement on the cores of an unheated (blue data) and a heated (black data) optical fibre. The heated optical fibre remained within a temperature range above 850^0C for approximately 90 days. **Figure 7** demonstrates the germanium weight concentration percentage of both heated and unheated fibres, after being fitted with a Gaussian function and then smoothed with a 10-point averaging. The weight concentration difference between the fibres is roughly 1%, which is less than the one shown in our previous results [7]. In addition, the measured FWHM of the heated fibre is 6.29 while for the unheated fibre is 4.86. This suggests that the germanium is diffusing towards the cladding of the fibre, due to thermal effects. The standard measurement error of the EDX scanning technique is ±0.1 Wt.%.

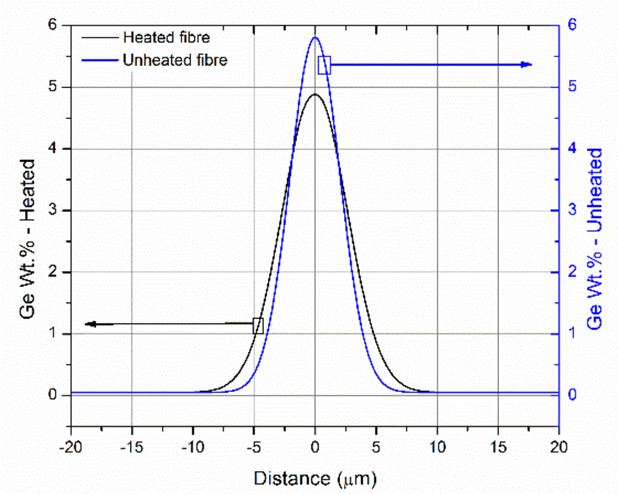

Figure 7. Line scan with EDX analysis technique of the heated (black line) and unheated (blue line) optical fibre (source: Dr Jim Buckman, Institute of Petroleum Engineering, Heriot-Watt University).

3. CONCLUSIONS

We presented an intrinsic Fabry-Pérot optical fibre sensor, of which its sensing element is made by a pure fused silica cavity. We have demonstrated long term (33 days) stability test and the cycling phase response. We have suggested that the modulations and drifts of our sensors' phase response is caused by germanium dopant diffusion, which gives rise to a second cavity signal. This interferes with the fundamental signal causing phase modulations within our desired signal. In addition, some preliminary results of dopant diffusion from the core to the cladding are presented. Our investigation of these phenomena is still on progress. Our continuing work will look into the practicalities and possibilities of a Fabry-Pérot sensor made by welding and cutting a sapphire disk on an optical fibre, and test them to temperatures above 1100^0C.

4. REFERENCES

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