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Effects of High temperature and Pressure on Silica Optical Fibres and the Implications on Optical Fibre Sensors.

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Abstract:

We report on the observed effects of liquids at high temperature and pressure on Silica optical fibres, sensors and gratings. We propose that the diffusion of molecules into the silica and the resultant expansion of the network are responsible for observed fibre expansions of upto 0.2% and bragg wavelength increases of 2nm at 1525nm. A developmental solution in the form of amorphous carbon hermetic coatings has shown a reduction of these effects by an order of magnitude at 300°C.

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Introduction:

The inherent benefits of many optical fibre sensors rely on the fact that the guided light is directly modulated by optical path length and refractive index peturbations of the "stable" silica waveguide. When the long term stability of silica is brought to question, the accuracy of such sensors also comes into doubt.

In this paper, we present recent results which demonstrate some of the problems of silica optical fibres as sensors in environments of high temperature and pressure and report on the need for suitable "hermetic " coatings for such devices.

By monitoring the pressure induced birefringence of a Side-Hole optical fibre with time under conditions of high temperature and pressure, we have found that the birefringence drifts considerably. This drift is increased non linearly with increasing temperature and the effect is permanent.

Removing the effects of the side hole fibre geometry from the investigation, the high temperature instabilities have been further investigated using Hi Bi fibre pressure sensors, fibre bragg gratings and standard telecommunications single mode fibre. Similar results for the drift of Hi Bi fibre birefringence, single mode fibre length and fibre bragg grating wavelength show that the observed effects are inherent to silica and are not due to geometry. It is therefore expected that similar effects will be observed for any silica interferometric sensor in such an environment.

Side Hole Polarimetric Fibre Sensor

Side hole fibre was proposed by Xie et al, [1], as a possible sensor for hydrostatic or acoustic pressure. In the presence of hydrostatic pressure acting on the outside of such a fibre, an anisotropic stress is induced in it's core due to the fibre geometry. The resulting birefringence can therefore be measured and continually monitored to provide an inferred measurement of pressure.

The pressure sensor consists of an input polariser, a length of side hole fibre and a mirror. The input polariser is aligned at 45° to the birefringent axes of the side hole fibre to couple approximately equal amounts of light into each axis. Under the application of hydrostatic pressure, a change in the group refractive index in each axis is produced through the photoelastic effect. The result is the generation of a fast and slow axis where n_f and n_s are the fast and slow group indices respectively. The magnitude of Δn, where $\Delta n = n_s - n_f$, is dependent upon the applied pressure and also upon the fibre geometry.

The pressure induced optical path difference between the birefringent fibre axes is monitored using a dynamically matched low-coherence interferometer in which the path difference is matched in a reference Hi-Bi fibre scanned in temperature.

Hydrostatic pressure is applied to the fibre by means of a dead weight tester through a liquid medium within high pressure steel tubing. The chamber temperature is varied as required using heating cord and is controlled and insulated.

Fig. 1 shows the results of two sensors at temperatures of 200 and 300° C where water has been used as the pressure medium. A pressure of 4000 psi has been permanently applied to the fibres. The resulting birefringence and corresponding pressure measurement are shown. The effect of temperature on the drift is very noticeable where increasing temperature has a disproportional effect on the drift rate. The drift is therefore not observed at room temperature as the rate of change in birefringence will be extremely low. For fibres at 300° C , there is a zero crossing on the birefringence/ pressure axis indicating that there has been an exchange of the birefringent fibre axes with the fast axis becoming slow and vice versa. This drift effect is permanent and therefore, as the initial zero pressure offset of the fibre is low, on removal of the pressure, the resulting side hole fibre is very highly birefringent (equivalent to a pressure of 6000psi) with a typical beat length of the order of 1.5 mm at 633nm. This can be reduced through HF etching of the fibre or by "drying out" in an oven at high temperature.

As well as the temperature effect on the fibre drift characteristic, the effect of the liquid medium has also been studied. Fig.2 shows some of these results, all at approximately 300° C. Other liquids have been used to attempt to remove all trace amounts of water from the pressure chamber. It is believed that water ingress into the outer layers of the fibre cladding results in the development of a highly stressed layer which exerts an opposing "pressure" on the core. This has been confirmed through the use of a finite element model (FEM) of the fibre in which the introduction of a swollen surface layer is capable of inducing such a highly birefrefringent fibre. It is interesting to notice that the water has by far the greatest effect on the fibre and for this reason, it is water that has been used for the majority of recent experiments.

Effect on Silica Fibres

In order to investigate the effect of the side hole structure of the fibres on the drift phenomenon, the pressure sensor experiment has been repeated using bow tie and panda hi-bi fibres as pressure sensors. The resulting birefringence, normalised to pressure, have been consistent with those for side hole fibre, indicating that the fibre geometry does not contribute to the drift. To investigate this further, measurements have been made using single mode fibre and fibre bragg gratings (negative index to prevent high temperature decay [2]). The proposed swelling of surface layers of a fibre is anticipated to produce an overall swelling of the fibre. The length of a fibre and also the braggwavelength of a grating have therefore been monitored under similar conditions to the side hole fibre. Lengths of carbon coated fibre have also been measured as a comparison to uncoated fibre and as a test of the coating hermeticity.

A length of carbon coated fibre, a length of standard telecommunications fibre and a negative index grating have been spliced to high pressure seals in both a dry chamber and a chamber containing water. The lengths have been measured using low coherence interferometry and the gratings were interrogated using an optical spectrum analyser and subsequent averaging of the spectrum to achieve a single bragg wavelength value. The lengths of fibre within the pressure chamber were all 1.8m with mirrored endfaces. However, only approximately 0.6 m of the fibre was in the hot area of the chamber.

Fig 3 shows the results for the length change of the fibre with time and fig.4 is that for the change in bragg wavelength with time. Both curves indicate that the same process is occurring for the two fibres. The sudden increase in length and bragg wavelength after 7 days occurred when the temperature of the chamber was lowered to 200°C and then returned to 300°C. This procedure was made due to the fading of the grating reflection. However, after the temperature cycle had been made, the reflection power had returned and the fibre length and bragg wavelength experienced sudden increases. This occurrence is being investigated further. These effects were not noticed in the carbon coated fibre or the fibres in the dry chamber.

On removal of the fibres from the pressure chamber after the experiment, the lengths of fibre were physically measured and were observed to have increased in length greater than the path length measurement of 1.1mm suggested. The length change and optical path length change mismatch indicates that there has been a decrease in the fibre index during the process. This effect is to be expected when a swollen cladding layer exerts a tensional stress on the fibre core.

The curve for the carbon coated fibres in fig.3 is of great interest as a solution to the problem of liquid ingress into optical fibres. The reduction of the effect by a factor of approximately 10, is strong indication that this problem can be, and is currently being solved.

Theory of Drift Process

It is the opinion of the authors that the drift phenomenon in optical fibres at high temperatures and pressure is due to the ingress of liquid molecules into the silica structure and the resultant disruption of the silica network. This disruption gives rise to an expansion of the glass and hence results in a tensile stress on the fibre core. In the case of the side hole pressure sensor, this is shown as a change in birefringence of the fibre due to the fibre geometry. For lengths of fibre and fibre bragg gratings, the result is the combination of a longitudinal strain and a decrease in the group refractive index of the waveguide which has the effect of masking the true magnitude of the fibre extension.

Modelling of this process using FEM shows that all the observed changes in the fibres can be explained by the swelling of a thin outer layer of the fibre. Also, during etching experiments on the treated grating and side hole fibres, the changes can be reversed. Fig.5 shows the results of etching of the two bragg gratings. The gratings were etched in a dilute solution of HF down to a radius of approximately 15µm. Little change in bragg wavelength is expected down to this fibre diameter [3]. This is true for the "dry" grating. However, the bragg wavelength of the "wet" grating has shifted considerably from it's offset value of 1526.39nm back towards it's initial (untreated) wavelength of 1524.49nm. This change continued to occur until the end of the etch experiment when the fibres failed at a measured diameter of 30µm. This would suggest that the water (or OH groups) had diffused almost 50µm into the glass. This value is much greater than previous authors have shown in bulk glasses during autoclave experiments [4] where a value for the diffusion coefficient of approximately $5 \cdot 10^{-13} cm^2/s$ has been given for 300°C. This would suggest that the average diffusion distance of a water molecule (or hydroxyl group) was approximately 8µm.

Conclusions

We have shown results which question the stability of silica fibres in high temperature and pressure conditions and have attributed this instability to the diffusion of the surrounding medium constituents into the glass. This has great implications on the use of optical fibre sensors especially in harsh conditions such as down hole sensing in oil wells. The long term drifts at lower temperatures are also therefore inevitable althought the effects are disproportionalely reduced with reduced temperatures. Finally, we present a solution to this problem with the use of and development of hermetic coatings, in this case carbon which has reduced the effects, observed in single mode fibre length measurements, by an order of magnitude at 300°C.

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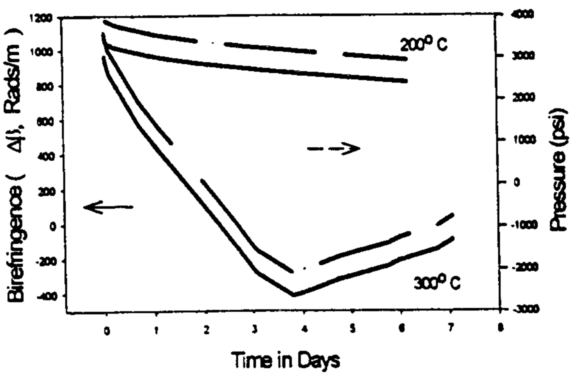

Fig.1: Side hole fibre birefringence (solid lines) and pressure drift (dashed lines) with time at 200°C and at 300°C in water under 4000psi.

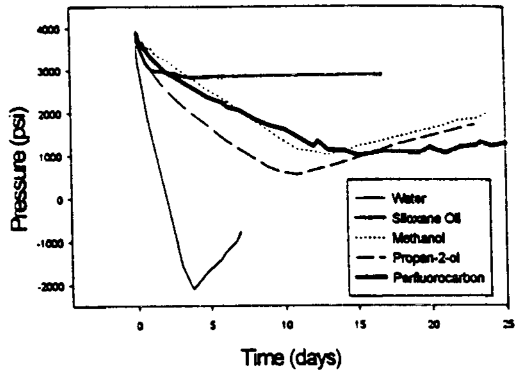

Fig.2: Side hole fibre pressure drift with time at 300°C in various liquids under 4000psi.

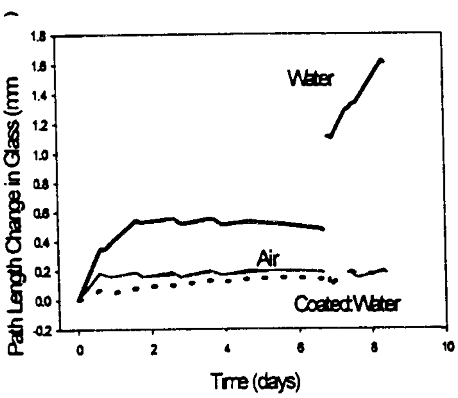

Fig.3: Length change of coated (dashed lines) and uncoated fibres (solid) in water and air at 300°C with time.

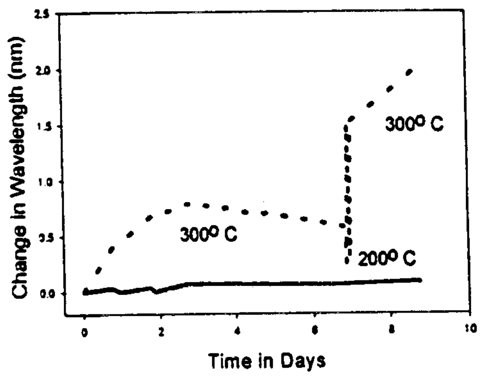

Fig.4:Change in bragg wavelength of fibre bragg gratings in water (dashed) and air at 300°C under 4000psi.

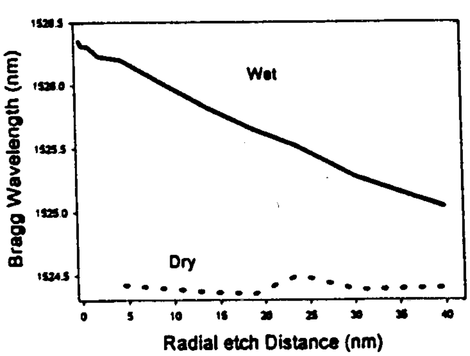

Fig.5: Change in bragg wavelength of water treated and dry treates (dashed) gratings during HF Etching.