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MULTI PARAMETER OPTICAL SENSING FOR HARSH ENVIRONMENT STATIC AND DYNAMIC PRESSURE SENSING CORRECTED FOR LARGE TEMPERATURE SWINGS

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ABSTRACT
We will report on progress made in interrogating harsh environment sapphire optical sensors (1100^{o}C) using the measurement of the temperature of the sensor itself to correct for cross sensitivity of the pressure signal to the temperature signal. Results will be presented showing real temperature and pressure data and the corrections obtained from an actual sensor. The constraints this puts on the optical source and the choice of cavity lengths to achieve satisfactory (low) crosstalk between the two parameters measured will be described.

Previous work has concentrated on correcting a static pressure against a changing ambient temperature of the sensor body: there are several locations in a gas turbine where the temperature is undergoing significant changes over sub-second timescales. This leads to unexplained noise in the dynamic pressure signal also, but Oxsensis' Multi Parameter Interrogation (MPI) technology allows for the temperature to be measured with the same speed of response as the pressure (up to 50kHz), and so affords the possibility of removing the error due to *dynamic temperature* effects. This data on temperature will in many applications, be useful in its own right, not just as a means of improving the sensor accuracy.

Using this technology, there is room for further improvement to correct for the fact that the temperature change may take a time to propagate through the sensor body, limiting the effectiveness of the correction. Modelled data will be presented showing this speed in simulated environments and explore methods of optimising this, with changes to the sensor geometry. Finally, we will turn our attention to the accuracy of such a scheme. Crosstalk between the cavities has already been highlighted as one issue, and will explore limitations on accuracy including the ultimate resolution of such a system, and the root causes of this.

In summary, performance data of a system to measure static and dynamic pressure with correction for temperature errors in a harsh environment, such as a gas turbine engine, in several important locations will be presented.

INTRODUCTION
Optical sensors to measure pressure in harsh environments are receiving serious consideration from the gas turbine world. Oxsensis has been producing such sensors for a number of years in response to the demand to measure dynamic pressure. It has become apparent that there are applications which require static pressure – which we take to include slowly varying pressure. The distinction has been made in the past because events such as combustor howl or other instabilities are monitored by looking at acoustic (20Hz to 20kHz or beyond) frequencies. Phenomena such as flame out and other parameters (such as compressor rotating stall) require quasi static pressure by which we mean pressures 20Hz down to DC.

Optical sensors have several advantages over existing electronic based sensors. These tend to be piezo electric or piezo resistive. The piezo electric will not offer a response down to DC, and the piezo resistive can measure static pressure but not at the elevated temperatures optical sensors offer. Electronic based solutions are limited to temperatures typically of the order 700°C, due to material and interconnect/thermal gradient constraints, whereas optical sensors in sapphire have been tested up to 1100°C.

To extend optical sensors to measure static pressure a method is needed to null out temperature effects, as the temperature will be varying at speeds comparable to slow pressure excursions so cannot be ignored as it can be when making acoustic measurements. In the past [1] Oxsensis has overcome this temperature sensitivity by limiting measurements to dynamic pressure. The technique used relies on the fact that at a given temperature whereas the absolute pressure reading will have a contribution from temperature, the *slope* response is the same at any temperature. If it is assumed that the temperature is static for the duration of a pressure reading (valid at acoustic frequencies) then the dynamic pressure can be recovered.

It is advantageous in many applications to overcome two problems; one is that temperature of the sensor can be measured and used to correct for the static pressure error due to temperature drift. The second issue is that there are some locations in a gas turbine (such as close to the combustor primary zone, or mounted on the combustor liner) where the temperature at the face of the sensor may also be varying at frequencies comparable to the frequencies of pressure one is looking for, or will appear as 'noise' on the pressure signal. This will swamp it, if one is looking for a weak signature of say 0.1psi, which for a 50Bar sensor represents a dynamic range of 70dB.

In this paper two main issues will be examined; first, the design of the interrogator to minimize errors between the two measurands; secondly, the thermal properties of the sensor head and the impact this will have on correction of effects due to fast changes in temperature.

This paper will describe the principles of multi cavity interrogation. In previous publications [1] the ability has been stated to measure multiple cavities without any further investigation of the issues involved. This paper will examine practical issues more closely.

NOMENCLATURE

SLD – superluminescent diode
PD – photodiode
MPI – multi parameter interrogator
DC – direct current, static
MZ – Mach Zehnder (Interferometer)
OPD – Optical Path Length
h – Convection heat transfer coefficient, $W/m^2.K$

MULTIPARAMETER SENSING: PRINCIPLES OF OPERATION

Consider a Fabry Perot sensor interrogated by a tunable filter such as a Mach Zehnder interferometer as shown in fig. 1

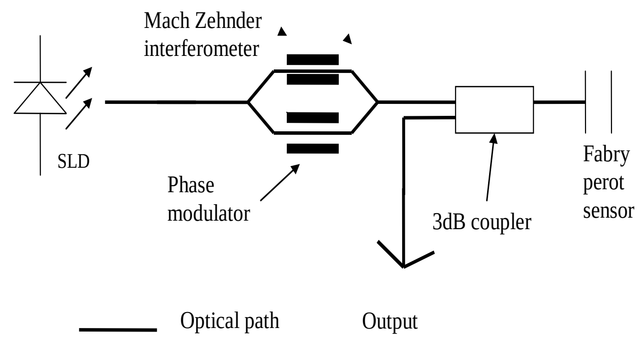

Fig.1 FP sensor illuminated by light filtered through tunable filter

If the sensor is illuminated by a wideband source, whose coherence length is shorter than the cavity length of the sensor a spectrally encoded signal is obtained, ie the broadband light has peaks and troughs in intensity for different wavelengths. The next figure shows the typical spectral response of such a sensor.

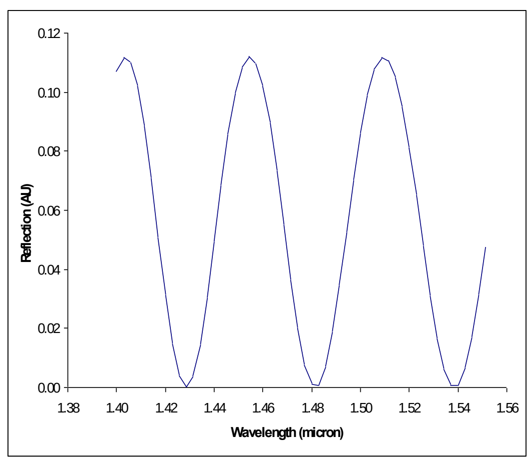

Fig.2 Wavelength response of sensor

In a real life sensor there may well be more than one cavity. The following diagram shows a typical sensor with three cavities, realized in sapphire. Sapphire is well known for its uses in harsh environments such as nuclear reactors and gas turbines, due to its consistent mechanical properties, high use temperature and immunity to chemical attack [2]

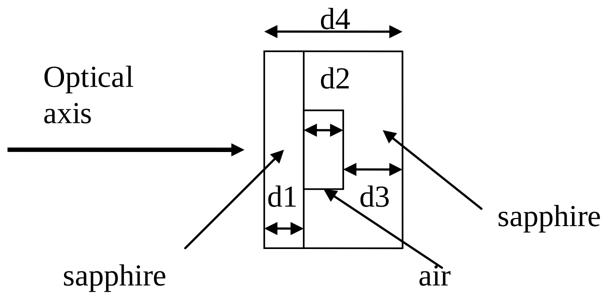

Fig.3 Multi cavity Fabry perot sensor.

The reflected spectrum of such a multi cavity sensor illuminated in a similar way to described above for the single cavity will give the spectrum shown in fig. 4 Whereas this spectrum looks somewhat unintelligible it does in fact contain information as to the sizes of the cavities present in the sensor. If one can interrogate this sensor in such a way as to obtain the cavity lengths independently one can measure the cavities and in the embodiment described in this paper measure pressure and temperature of the sensor independently.

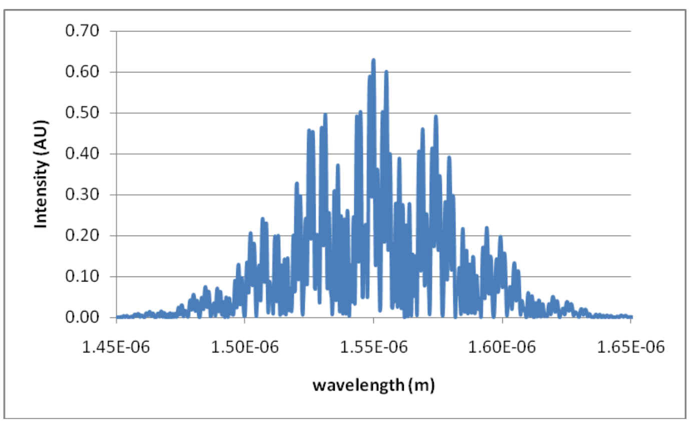

Fig.4 Multi cavity sensor spectrum.

If one looks at the output signal from the set up shown in figure 1 as the MZ OPD is varied across a range which includes more than one cavity length a result as shown in fig.5 is obtained.

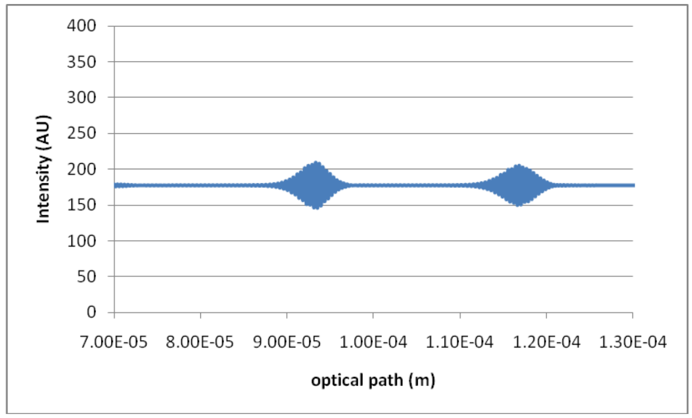

Fig. 5 Correlation function with two cavities

It will be seen that for each cavity there is a set of fringes contained within an envelope. If the cavity lengths are not sufficiently separate the two groups of fringes may interfere and the result is that there will be crosstalk between the two cavities. Options to manage this crosstalk are examined in the next section

OPTIMISATION OF INTERROGATOR RESPONSE

Let us examine the sensor pill of fig. 3 in more detail. The sapphire thickness labelled d3 is the layer of sapphire chosen to flex with applied pressure, thus varying the cavity shown by d2. The sapphire will expand with temperature and both d3 and d2 will expand. This expansion causes the temperature cross sensitivity me have mentioned. The expansion in d3 is used as a temperature-only measurement which can be used to correct for the thermal expansion of the pressure cavity. It has been mentioned already that one method of minimizing crosstalk between the variation of the two cavities is to make d2 and d3 suffficiently different. Whereas this seems an obvious solution, it may not always be practicable in a real sensor. For example in the example cited above the diaphragm thickness is mainly dictated by the response the sensor is required to have to pressure, and this may dictate the diaphragm being too thin to give a cavity sufficiently large to be far enough away from the cavity used to measure pressure. Also constraints due to the sapphire machining place a limit on what is achievable in size of d2.

The width of the envelopes also depends on the width of the input light source. Figure 6 shows the effect of an input spectrum width of 25nm, as opposed to the 50nm used in fig. 5. One can clearly see that the two groups of fringes are no longer distinct at this linewidth. This means that the cavity lengths can be closer together with broader band light sources.

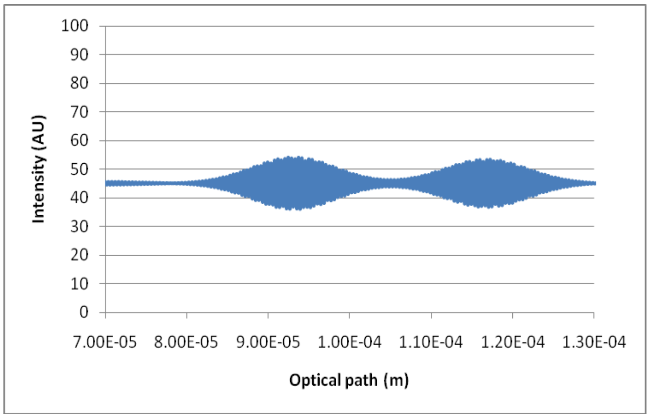

Fig. 6 Effect of 25nm source bandwidth

SLDs are commonly available at wider widths such as 100nm so the use of such devices allows the crosstalk to be reduced. Simulated results suggest 30ppm crosstalk for 100nm width. Actual measurements were also taken with a dual cavity sensor of the type shown conceptually in fig. 3. The sensor was exercised over pressure and temperature independently. A GE Advanced Modular Calibrator model DBI620 was used to apply the pressure to the sensor and the temperature was monitored by a thermocouple. The change in perceived temperature due to a full scale change in pressure is 0.6%. This is higher than the simulated result of 30ppm (which itself is limited by the numerical precision of the model used), and is limited in the noise floor of the temperature measurements. It is important to note, however that the fundamental principle permits low crosstalk between the parameters to be measured.

A graph showing the pressure excursions and the effect on the temperature readings is shown in fig. 7

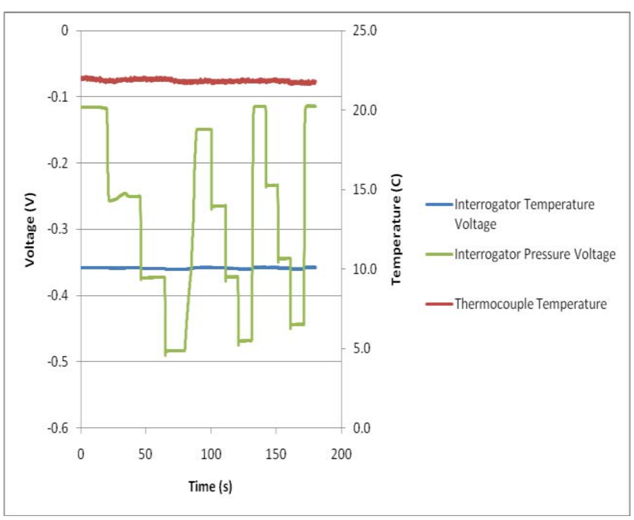

Fig.7 Pressure and Temperature test.

The results so far show that the optical interrogation system can measure two parameters, namely pressure and temperature of the sensor head, but to ensure that the temperature measured can be usefully applied to correct for the cross sensitivity of the pressure due to temperature, one needs to now look at the temperature distribution in the sensor head.

TEMPERATURE DISTRIBUTION IN SENSOR HEAD

We have described the technique of using interrogation of more than one cavity to allow the temperature of a pressure sensor to be used to correct for the cross sensitivity to temperature. So far we have limited discussion to situations where the temperature of the sensor can be assumed to be slowly varying in that the temperature of the sensor can be considered uniform. In some applications the temperature fluctuations can be fast – this has been seen in optical sensors designed to measure dynamic pressure that demonstrate a higher noise floor than expected due to rapid temperature fluctuations appearing as a dynamic pressure signal.

We performed some modeling of heat flow in sapphire to ascertain the frequency of temperature excursions that will allow our scheme to work. If the temperature of the sapphire can be considered uniform, ie the temperature measured by the front cavity is representative of the pressure sense cavity, then the correction assuming they are at the same temperature will work accurately.

We modelled the temperature of the sensor pill subject to a thermal stimulus on its front face, to give us an estimate of the speed at which the sapphire pill reaches thermal equilibrium after its front face is subjected to a temperature impulse. This sort of thermal modeling taking into account the conditions inside, for example, the combustor of a gas turbine is a complex subject, and we are going to present a very simple estimate to justify the validity of our temperature correction approach.

We will begin by describing the thermal model we used. We treat the sapphire sensor as a semi infinite body as shown in fig.8.

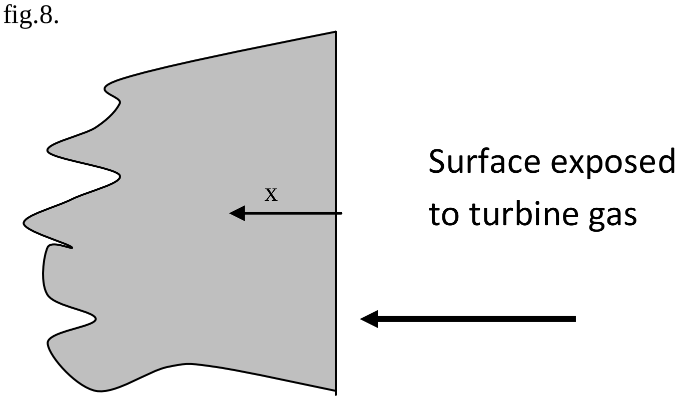

Fig. 8 Section of semi infinite piece of sapphire

In figure 8 above the grey area represents sapphire and the wobbly line shows an artificial boundary as is customary in schematic drawings. It depicts a body of sapphire of infinite extent to the top, bottom and left of the figure, with a boundary facing the turbine gas, which is to the right. Another way of clarifying this is to note that since a semi infinite body in principle extends to infinity in all but one direction, it is characterized by a single identifiable surface which is the vertical boundary between white and grey in fig. 8. The arrow labeled 'x' is the distance x into the body from the boundary. The reason for choosing such a geometry for consideration is that it gives a good insight into the temperature gradient at a given distance from the surface exposed to the gas, and so will allow one to ascertain the efficacy of the method of measuring the temperature at one point in the sapphire in real time to correct for the temperature of the pressure sensor portion of the sapphire. For the method to work it is necessary that over the time scale of interest the temperature is essentially the same at the two locations. An analytical solution exists to this situation [3], whereby it is possible to calculate the temperature as a function of time and distance from the boundary for a body of sapphire at an initial temperature T_i, exposed to a gas temperature T_∞ which we evaluate for the situation of interest, assuming all the heat is transferred by surface convection. The analytic solution is :

$$\frac{T(x,t)-T_i}{T_\infty - T_i} = erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) - \left[\exp\left(\frac{hx}{k}+\frac{h^2\alpha t}{k^2}\right)\right] . \left[erfc\left(\frac{-x}{2\sqrt{\alpha t}}+\frac{h\sqrt{\alpha t}}{k}\right)\right] \quad (1)$$

Where $T(x,t)$ is the temperature in the sapphire as a function of position x and time t, T_∞ is the temperature of the gas, T_i is the initial temperature of the sapphire body, α is the thermal diffusivity in m^2/s, h is the convection heat transfer coefficient of the gas in $W/m^2.K$, and k is the thermal conductivity in $W/m.K$

Given that the situation is axially symmetric and that the thermal conduction of sapphire is fairly close to that of a metal, we consider it reasonable to use this method to estimate the temperature gradient and its speed of conduction in the sapphire provided one has a convincing value for the convection coefficient, h, between the turbine gas and the surface of the sapphire. There is a discussion on values of h for typical gas turbine conditions of 1300K to 1600K and pressures of 300psi in the HP and IP stages in [4]. We chose a value of h of 5000 W/m^2.K . This is considerably higher than the natural convection coefficient of air at atmospheric pressure which is generally accepted as 100 W/m^2.K [3] . The value of this parameter has a marked effect on the temperature distribution and the time response of the body exposed to the gas. If h is low then the temperature of the sapphire will rise slowly, but for a given depth into the sapphire the temperature will be uniform. If h is large the surface of the sapphire will heat up but there will be finite time for the temperature to propagate through the sapphire. This regime would mean that the temperature measured by the front cavity of the sensor would be different to the temperature of the pressure cavity. To assess the validity of these assumptions and to give a worst case scenario it is necessary to model the limiting case where the sapphire surface of the sensor is subject to an infinite source/sink. This analytic model is based on Fourier expansion of the heat equation [5]. Consider a piece of sapphire 1mm long, the far end of which is attached to a constant temperature, and the end exposed to the source is suddenly heated to 1000K. The graph in fig. 9 shows the result.

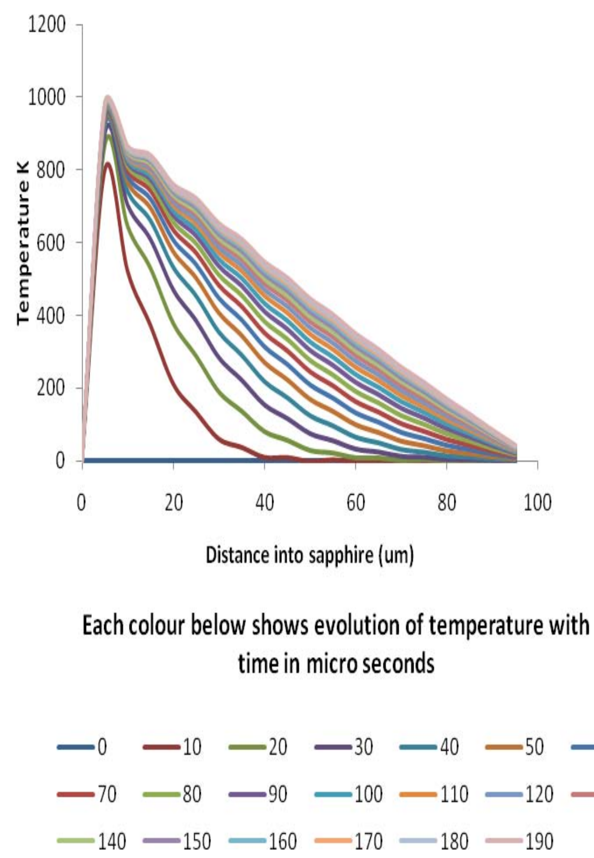

Fig. 9 Evolution with time of temperature gradient in a sapphire body against distance into sapphire

Figure 9 warrants some explanation. The distance along the x axis is the distance *from the sensor front face*, and the bottom curve on the graph shows the temperature distribution after 5 μ s; ie the temperature has only risen to 50% or 400K after 20 μ m, whereas after 190 μ s (the top curve) the temperature has reached 50% of the excitation 50 μ m into the sapphire. This suggests that temperature correction is limited to under 5kHz. It should be borne in mind at this point that this is the worst bound of operation as this is effectively an infinite value of heat transfer, which means that the temperature of the sapphire is changing more rapidly than the temperature can reach equilibrium in the sapphire, so if the gas temperature fluctuates rapidly, as it might in some parts of a gas turbine, the correction applied to the pressure signal will be out of date, and this will be worse the farther apart the temperature sensing cavity and the pressure sensing cavity are. Returning to a more realistic situation with a value of h =5000 W/m^2.K, one can evaluate using equation (1) the temperature of the sapphire as it develops with time for the same situation described above but with the heat reaching the sapphire by convection from the gas flowing past the sensor as one would expect in a gas turbine location.

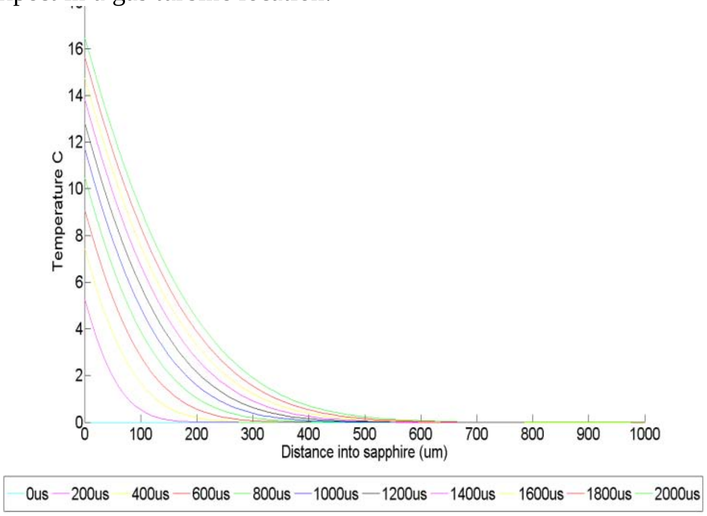

Fig.10 Temperature evolution at 1 and 1.1mm into sapphire

The graph of fig. 10 is superficially similar to fig. 9 but close inspection of for example the behaviour 300 μ m into the sapphire shows that the temperature at 800 μ s (blue) doesn't reach 400 μ m (second magenta) until 1200 μ s ie 400 μ s later. It should be noted that the temperature error is only of order of 1C, so error correction of 0.02% is possible. There is clearly a tradeoff between distance between the sensing points and the degree of correction available for a given speed of temperature excursion. For the sort of conditions experienced in a gas turbine it should be possible to obtain a meaningful static and dynamic pressure corrected for cross talk from temperature fluctuations. It is anticipated that the Author will be in a position to verify these simulations in the near future Further work will look at more advanced modeling to obtain more accurate results, although as already mentioned this would require a more accurate information concerning conditions in the environment the sensor is expected to operate.

ACTUAL SYSTEM REALISATION

This paper has concentrated on the concepts involved, but for completeness it includes a description of the actual sensor system realised.

Using Oxsensis proprietary techniques the sensor pill similar to that described in fig. 3 has been packaged. This means that, in common with our other sensors that it is suitable for use in harsh environments at temperatures in excess of 1000^{o}C. The results shown in fig. 7 were obtained with such a sensor, the optical and electronic set up described has also been made into a production prototype, figure 11 shows the packaged optical interrogator chip.

Fig.11 Packaged Mach Zehnder interferometer

The sensor suitable for measuring both pressure and temperature is indistinguishable from a single parameter sensor, but again for completeness, and to demonstrate that the ideas in this paper have made it from concept to reality, fig. 12 shows two sensors, the colouration resulting from the high temperatures at which they have been tested.

Fig. 12 Actual production sensors

CONCLUSIONS

This paper has described how measuring the temperature of a sensor whilst it is measuring temperature can be used to correct for errors due to expansion of the pressure measuring cavity. This description includes progress made on a multi parameter optical interrogator to allow both cavities to be measured in real time down the same optical fibre.

Additionally the consequences of rapid temperature fluctuations have been examined, and through some simple modelling, it has been demonstrated that the temperature excursions of the sensor head in a real environment are slow enough for the sapphire to be considered to be at a sufficiently uniform temperature for the correction scheme outlined to be viable.

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