Optical Fiber Fluorescence-Based Sensor Techniques for High Temperature Measurement

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Abstract

In this work, a number of techniques for high temperature sensing and measurement, especially those using a low-cost fluorescence-based approach, are reviewed, results are presented and compared and contrasted. Applications in a number of engineering sectors are considered, and examples are given of trials of such sensors for industrial monitoring.

Keywords: optical fiber sensor, temperature sensor

1. INTRODUCTION

Temperature monitoring has been a very important process in various industries for many years, and active temperature compensation of other measurements e.g. strain, pressure and flow is essential if accurate data are to be presented. Many methods of temperature sensing have been used and the thermocouple remains a cheap and effective device for very many simple sensor applications. However, there are situations in both the industrial and bioengineering fields where simple electrical monitoring methods are not suitable and here fiber optics offer a potentially convenient solution to this important measurement need. The advantages of the use of fiber optic systems in measurement have been spelt out elsewhere [1] and the increasing availability of components "spun off" from the telecommunications industries and the falling price of fiber and the associated signal processing systems make these measurement systems increasingly attractive to the sensor designer. In this work a number of fiber optic-based temperature sensor systems, especially those developed by the authors using fluorescence-based techniques are discussed in light of a range of applications where high temperature measurement is needed, and where fiber optic schemes offer potentially better solutions than through the use of conventional methods. Results are reported on their performance and comment is made on the suitability of the systems for the uses envisaged.

2. INDUSTRIAL APPLICATIONS OF FIBER OPTIC TEMPERATURE SENSORS

A number of applications have been discussed in the literature [2] and it is worthwhile to highlight several of these where the fiber optic approach is particularly important. They include:

- Transformer monitoring to recognize “hot spots” by winding a fiber optic sensor within the transformer, or retrofitting the sensor into the device e.g. in the transformer oil
- Engine combustion monitoring, especially in turbine engines to enable a better understanding of the combustion conditions, with the aim of efficiency and lifetime optimization
- “Smart structures” and structural integrity, to determine structural changes with temperature, in monitoring processes such as concrete curing and building corrosion monitoring and control
- Furnaces and kilns, to improve combustion and efficiency and increase the lifetime of kiln linings, whilst minimizing the furnace “down-time" and consequent production loss

- Fire alarm systems, to monitor conditions of rapid temperature excursions due to fire and restore standby conditions when the temperature falls below the system reset level
- Process industries e.g. chemical plant, where monitoring of temperature for both production efficiency and enhanced safety is essential, especially where a non-electrical system may be used to avoid "spark hazards"
- Sewers and drains, where explosive gases my be formed and electrical sparks must be avoided
- Temperature compensation, where the correct data from a sensor system is dependent upon a true knowledge of the environmental temperature, with monitoring potentially over a wide range from the cryogenic to the very high temperature regions Other applications excit and undoubtedly will be developed – fiber optic systems have the versatility to cope with a wide range of both current and future needs.

3. THE OPTICAL FIBER TECHNOLOGY INVOLVED

In this work, sensors involving fluorescence-based methods are considered – a range of other techniques has been reviewed [3] elsewhere and their comparative value discussed. Distributed techniques are not, however, considered in any details in this paper. They have been discussed both in principle and in terms of a number of important topical applications in an article by Hartog [4]. Clearly their uses are closely related to the special features they offer – the ability to make a measurement at any point along the fiber length, to a resolution usually of a few degrees Celsius, or better – but at a cost that is frequently much higher than other sensor schemes, both optical and conventional. Stimulated Raman and Brillouin scattering schemes are discussed extensively in the literature [5], the latter offering the potential for measurements over many tens of kilometres. The signal processing schemes and the optical configuration are, by the nature of the interaction, complex and a limiting factor for may possible uses.

The fluorescence-based systems discussed are used here for either *point* or *quasi-distributed* sensors, where the measurement is made either at a point (usually at the end of the fiber) or at pre-determined and pre-sensitized points along a fiber network (usually where a section of sensitive fiber has been spliced in). Temperature excursion along the whole fibre length can be addressed quickly if the detailed location of the excursion is not critical in the sensing loop. The essential optical technology used, illustrated schematically in Figure 1 is simple – a commercial laser diode source and detector, usually operating over a wavelength band in the red or infra red part of the spectrum, an optical coupler (or wavelength division multiplexed (WDM) splitter) and a signal processing system, either built in hardware or designed using a proprietary visual programming system (HPVEE or LabView). In this way the change in the experimental decay of the signal from the sensor can be determined, and the result recorded and compared to data from a previous calibration to yield the temperature(s) required. A schematic of a simple Er-fiber based probe is shown in Figure 2, where the system is excited at approximately 980 nm and fluorescence spectrum is centred at approximately 1550 nm. Using a similar optical arrangement, a fluorescence intensity ratio (FIR) approach may be used [6] and the comparative merits of the two techniques has been discussed by Collins et al [7 and references therein]. In this latter method, the fluorescence emission on two bands is studied and a ratio, sensitive to temperature, obtained and calibrated as a function.

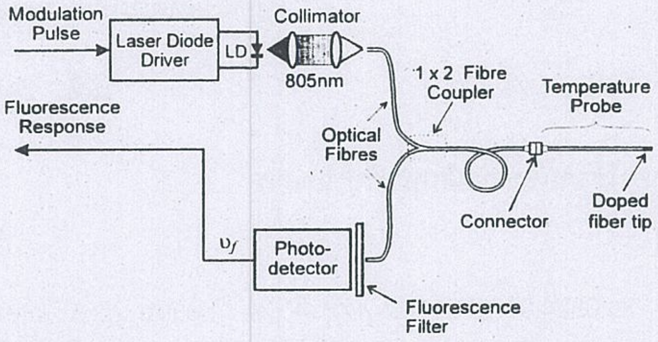

Figure 1 Optical arrangement of fluorescence based technology.

A key issue for the use of optical fiber in such systems is the maximum temperature a fiber can stand. Normal clad "telecom" fiber is rated to approximately 150°C but commercial metal coated fiber is specified for use to approximately 600°C, or slightly beyond with the more expensive gold coating. Electroplated nickel fibers with thicker coatings (due to multiple layers being built up) can be used up to approximately 1000°C but beyond approximately 1100°C the fiber tends to crystallize and crack and is rapidly rendered unusable [8]. Beyond these temperatures, non-silica materials such as sapphire and garnets are better but sapphire fiber is expensive, unusually unclad and only available in short lengths (a few meters) at a much higher cost [9]. Plastic or polymer optical fiber has enhanced flexibility, may be doped and is relatively rugged but the nature of the material limits its use to approximately 150°C at maximum. The sensor designer must balance the advantages and disadvantages discussed above with the costs involved to achieve the optimum solution to the problem of effective sensor performance.

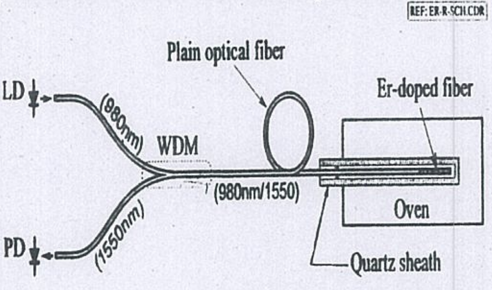

Figure 2 Erbium-doped fiber temperature sensing system.

4. APPLICATIONS IN HIGHER TEMPERATURE SENSING

Figure 3 shows the performance characteristic of a typical optical fiber sensor probe, in the style of that in Figure 2, over the range from room temperature to 1000°C. The characteristics of the fiber treatment and preparation are given in detail elsewhere [9] but in this illustration three different samples, each of different dopant level are shown. The curves follow the same pattern, but are displaced due to the influence of the doping level on the fluorescence lifetime. The typical fluorescence intensity observed (normalized to unity at room temperature) is also shown – this is not strongly affected when the temperature is lower than 600°C.

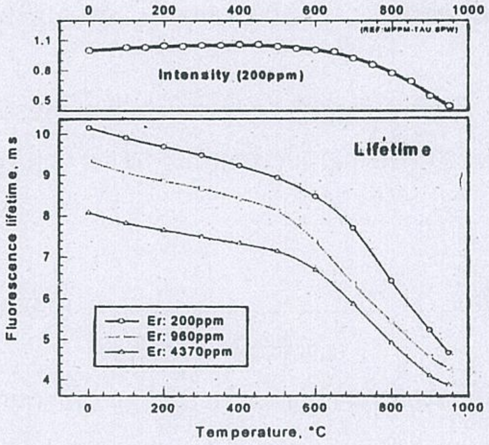

Figure 3 Thermal characteristics of Erbium doped fibers

Engine Testing

An innovative application of a sensor of this type is shown in Figure 4, using either Er and Nd in a sensor probe tested on a commercial aeroengine design (in this case Nd was used). A conventional thermocouple housing unit was modified to incorporate the optical sensor probe and it was installed on the engine. Performance data are shown in Figure 5 – a wide range of temperature was measured, up to approximately 700°C, with an uncertainty of approximately ±3°C, and satisfactory for the application. The measurement was seen to follow that of the thermocouple system, and show its capability to replace it, especially in conditions of high e.m. radiation interference and noise present in the detection system.

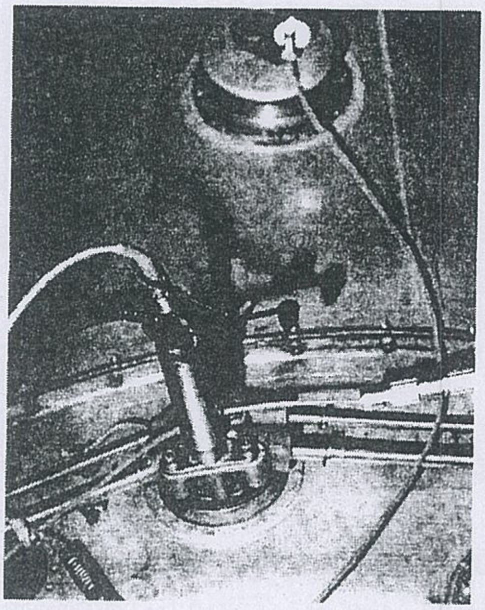

Figure 4 Sensor probe in aeroengine.

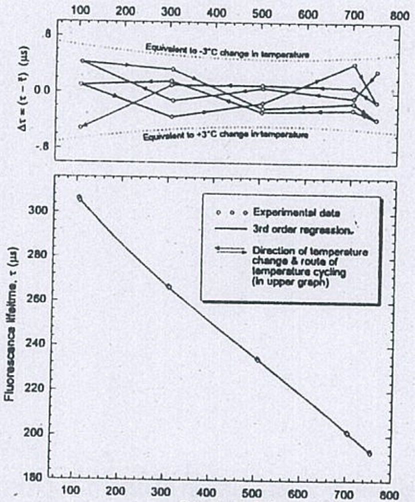

Figure 5 Performance characteristics of the sensor in aeroengine.

Exotic Crystal Fiber

Sapphire fiber offers the potential for higher temperature operation and doped sapphire is familiar as ruby. Such fiber is drawn by a process involving laser heating of the material source rod and a single crystal "seed" fiber used, as discussed by Sharp et al [11]. In this way fibers with a tip of ruby, or a similar material such as Nd:YAG, can be grown on to a single crystal fiber of the undoped material. The performance of such a system is shown in Figure 6 – although ruby is a less suitable material for very high temperature *measurement* (to approximately 550°C is a reasonable limit), the *survivability* of the fiber at much higher temperatures and the integrity of the measurement are very important. Recent work has shown that a ruby tipped sapphire fiber survives well at 1400°C with a reproducible performance characteristics, and such fiber is stable and reliable. However, it is only available in short lengths, usually unclad and is expensive (several hundred dollars per meter) due to the production process. It is however, an area where work is continuing, especially for monitoring in kilns and furnaces where the electromagnetic interference or nuclear radiation is present.

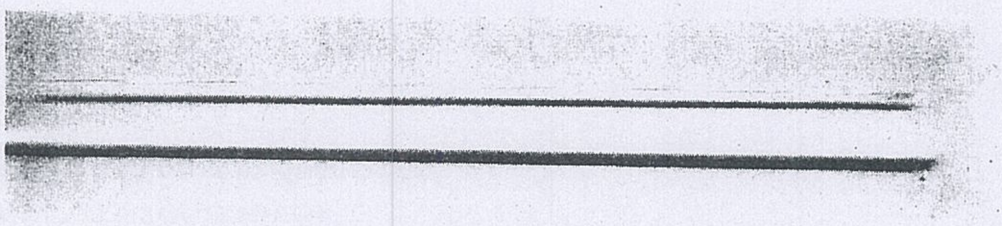

Figure 6 A single crystal ruby fiber.

Temperature Monitoring in Composites

It is often important to monitor the temperature in composite materials, such as are used in aerospace and aircraft components, both to determine the nature of the "cure" process and to monitor the system generally. This is of special importance when strain monitoring systems are introduced e.g. the use of a fiber Fabry-Perot (F-P) interferometer, in-line, for strain determination. Work of this type has been reported by Liu et al [12] where the temperature compensation data were provided for the F-P sensors using a neodymium-doped compensation fiber spliced into the network close to the F-P sensor itself, shown in Figure 7. This work revealed a small residual strain effect in the Nd-fiber: this has been investigated in some detail for Nd and similar doped fibers, and results have been reported by Sun et al [13]. This both offers the opportunity for a new type of strain sensor and provides a simple compensation mechanism not only for F-P sensors, but for Bragg grating based strain multiplexed systems with which the scheme is highly compatible.

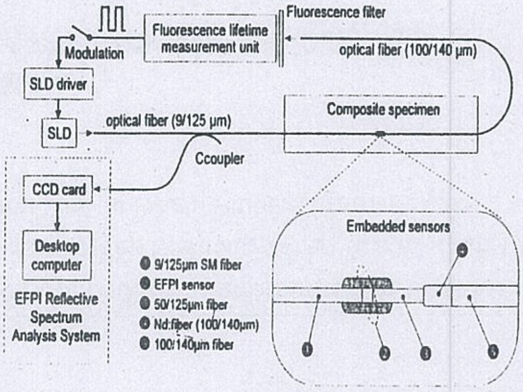

Figure 7 Strain and temperature measurement using interferometric and rare earth doped fiber sensor technique for composite materials.

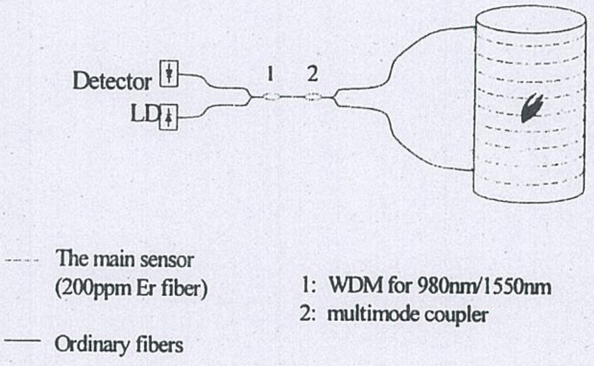

Figure 8 The schematic of the fire alarm sensor.

Fire Alarm System for Aircraft Engine Fire Detection

The fire alarm system designed by the authors has been targeted for aircraft engine fire detection and is required to be sensitive over the whole sensing length (1 m~ 3 m) up to a maximum temperature of 500~600°C. The sensing system is of a simple construction, as shown in Figure 8, where only one laser diode (980 nm) and one photodetector (InGaAs) are employed. The lifetime of the fluorescence signal, produced by the Er doped fibre, is sensitive to the temperature over the whole fibre sensing length. When one section of the fibre is exposed to the temperature excursion, the fluorescence signal will show a double exponential form which can either be indicated directly (by the differential method or the referential method [14]) or interpreted specifically to relate to temperature information by using signal deconvolution [15], discussed in detail by the authors elsewhere. In Figure 9, the temperature excursions (or hot spots) have been indicated as signal peaks (using the differential method) regardless of the background temperature drift caused by effects such as electrical noise or background temperature fluctuation. In Figure 10, a threshold can be set between "no alarm" and "alarm condition", no matter where the hot spot is (A and B in the figure show the random appearance of a hot spot). An alarm condition is indicated by the lifetime drift being either above or below zero, as seen in Figure 10, and with no hot spot, irrespective of background temperature, this lifetime drift is zero (Figure 10: middle). However, with a hot spot at points A or B (Figure 10: upper and lower respectively) the lifetime drift is either positive or negative respectively, irrespective also of the background temperature. In that way an alarm condition can be recognized.

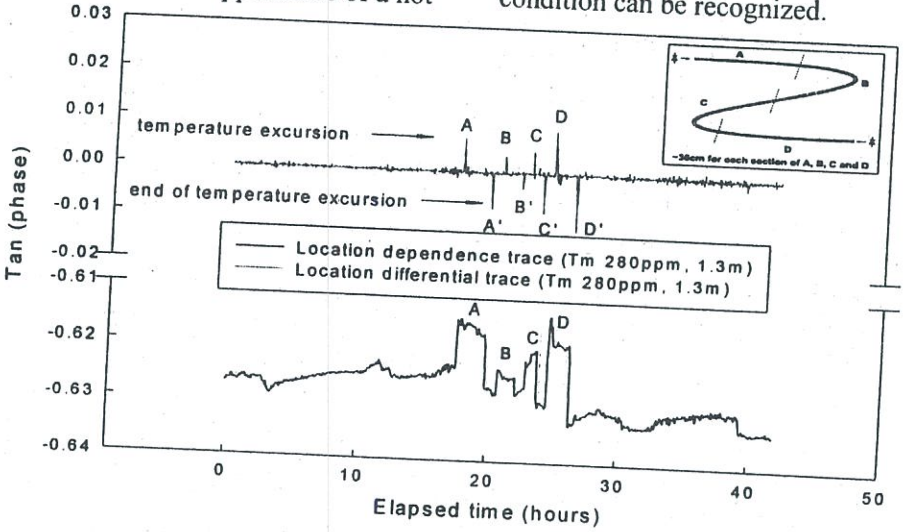

Figure 9 Temperature excursions are indicated as signal peaks (upper diagram) regardless of the background drift, seen in the lower diagram.

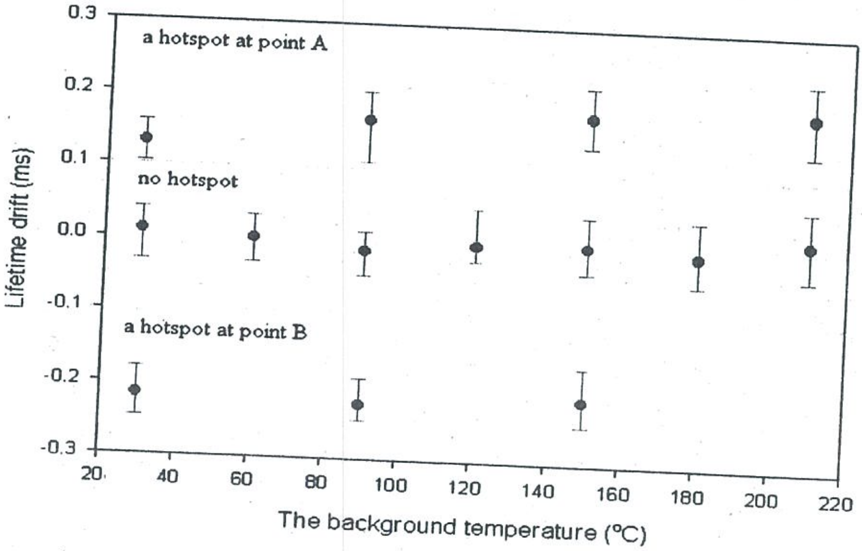

Figure 10 Illustration of the referential method (upper and lower traces show hot spots, irrespective of background temperature change).

Dual sensor for strain and temperature measurement

Three different types of sensor configurations have been tested, shown in Figure 11, for strain and temperature measurement by multiplexing the rare-earth doped fibres with fibre Bragg gratings. Sensor 1 shows a grating attached to a plain fibre, and sensors 2 and 3 are constructed with gratings written into the fibre itself. In this way the temperature and strain sensors are easily co-located in the fibre. These sensors have been tested and the results are shown in Figure 12, where after strain or temperature compensation, the results match well with the calibrated signal.

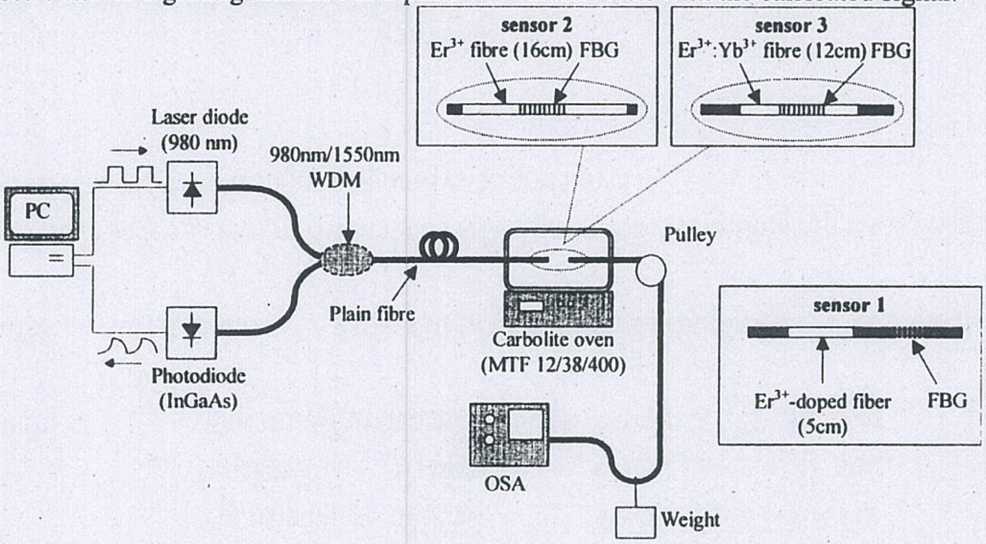

Figure 11 Dual sensor for strain and temperature measurement.

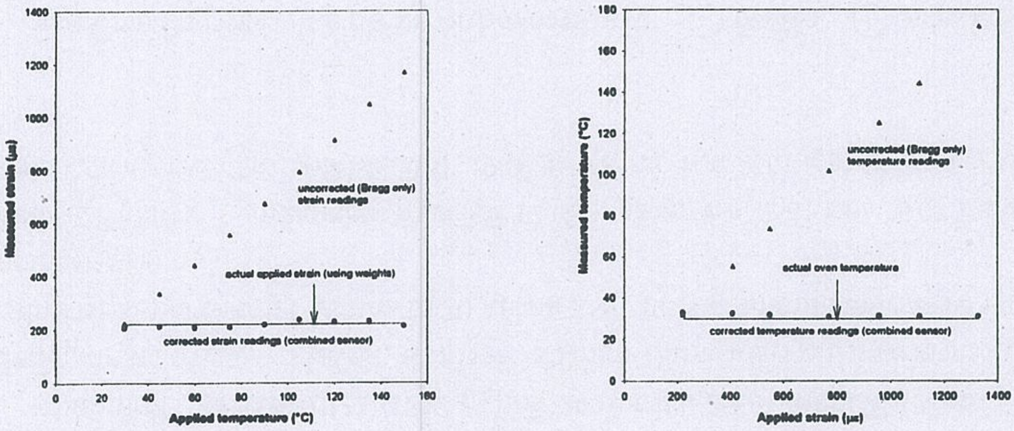

Figure 12 Strain or temperature compensation
using the sensors in Figure 11.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge support from EPSRC through the Structural Integrity Initiative, and other schemes including the Faraday INTErSECT Partnership and both personnel and equipment.

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