Silica Optical Fibre Based Temperature and Strain Sensors

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Abstract

This paper reports on work done with a range of silica fibres, doped with several important rare earth ions such as Er, Nd, Yb and Tm, to create a range of novel optical sensors. The approach reported herein is based on monitoring and analysis of the fluorescence decay from such fibres in the time domain as well as in the frequency domain. With these fibres, temperature sensors operating in the range from as low as -200 °C to beyond 1000°C have been constructed. A temperature resolution of the order of a few degrees Celsius has been typically reported from these types of sensors. Fibre of this type has been used in a simple yet effective structural integrity monitoring system (having been incorporated successfully into concrete samples) and an optical fire alarm system with potential applications for engine monitoring has been developed. A further recent discovery is a small level of strain sensitivity in such fibres – this has been explored over the region from 0 to 2000$\mu\varepsilon$, showing a level of resolution better than a few tens of microstrain, but the temperature and strain information can be addressed simultaneously by incorporating Fibre Bragg Gratings (FBGs) in the fibres. Very recent work has shown the potential of this type of intrinsic yet dual sensor for a wide range of temperature and strain measurement.

Keywords: Rare-earth doped fibre sensor, fluorescence decay, fibre Bragg grating (FBG), strain sensor, temperature sensor.

1. INTRODUCTION

With the wide availability of a range of types of rare-earth doped or photosensitive silica optical fibre, the opportunities for new lasers and fluorescent sources for communications and sensor schemes have been considered by a range of authors. Such fibres, most commonly seen in the erbium-doped silica fibre which is widely used in optical amplifiers (the familiar erbium-doped fibre amplifier, the EDFA) are robust, relatively easy to produce and on the whole, inexpensive. In recent years optical sensor systems designers have been able to exploit such fibre for different purposes from the communications systems for which they were originally developed – the creation of a suite of measurand-sensitive devices to monitor pressure, temperature and strain over a wide range.

A major priority for the effective monitoring systems for so-called 'smart' structures (structures which are enhanced by the inclusion of sensor devices) is the need to make multiple and often simultaneous measurements of strain and temperature within the structure and the cross-sensitivity of many strain monitoring sensors to temperature is a particular limitation in making effective use of such devices. A number of schemes have been proposed for temperature-strain discrimination using optical sensor systems and these have been reviewed, for example by Jones [1], indicating several different possibilities (some being more practical than others) for such sensors. Often such systems are complex and relatively expensive to implement, and methods which are intrinsic to the fibre (based upon in-fibre devices), including Fibre Bragg Gratings (FBGs) are to be preferred, to avoid for example, the phase ambiguities inherent in interferometry and exploiting their compatibility with wavelength division multiplexing to enhance the number of sensors which may be used. However, several multiple grating methods [2] and other grating techniques e.g. using long period gratings which may be considered for this type of monitoring show difficulties in the close defining of the sensing element. One simple solution proposed in this work is to write FBGs on rare-earth doped fibres to create a simple yet intrinsic dual sensor, from which the fluorescence as well as wavelength signals generated can easily be used to record the temperature and strain simultaneously and separately.

In recent studies, a wide variety of luminescent materials, in a number of different media, have been used to create a series of temperature sensors based upon the measurement of the temperature-dependent characteristics of their fluorescence emission. Such sensors can, in principle, cover a wide temperature range from the cryogenic (–200°C) to that above 1000°C [3][4][5]. In their creation, species such as Cr^{3+}, for example in ruby and alexandrite [6] [7], Pr^{3+} in ZBLAN [8][9], Nd^{3+} in glasses [10], garnets (YAG) [11] and Nd^{3+} [12], Er^{3+} [13][14], Yb^{3+} [15] and Tm^{3+} [16] in fibres (both silica and crystal) have been explored giving a wide range of device sensitivities over varied parts of this wide temperature spectrum. Two primary methods of fluorescent signal analysis have been found to be the most successful in temperature sensing, i.e. the intensity and decay-time based approaches, and their comparative performance characteristics have been discussed in an informative paper by Collins et al [17].

Optical thermometry research based upon fluorescence emission in Er^{3+}:Yb^{3+} doped glasses or fibres was discussed by dos Santos et al [18] and Lai et al [19]. The optical system employed was somewhat complex or based upon the use of amplified spontaneous emission (ASE), in which the use of an *optically amplified* signal shows some promise. A lower cost solution favoured by the authors [12] and used in this work involves the monitoring of the fluorescence decay time, which is a temperature dependent parameter which may readily be exploited.

The possibility to extend the fibre Bragg grating sensing range has been reported very recently by the University of Southampton [20]. Measurements up to ~800°C have confirmed the long-term thermal stability of Bragg-gratings written in tin-doped silica fibres and demonstrated a significant advantage over gratings written in conventional photosensitive fibres. The authors have started to explore in this work the maximum thermal capability of the gratings written in conventional photosensitive fibres or rare earth doped fibres by changing the writing parameters of UV lasers.

This paper reports on research carried out with a range of silica fibres, including Er, Nd, Yb and Tm doped systems. With these fibres, temperatures up to a full dynamic range of over 1200°C have been measured, with typically a resolution of the order of a few degrees Celsius. Fibre of this type has been used for concrete temperature monitoring during its curing process and also been used in a simple yet effective optical alarm system, with potential applications for aeroengine monitoring. A further recent investigation on the intrinsic sensor incorporating FBGs in photosensitive fibres or rare-earth doped fibres has extended the potential for wide range of temperature and strain measurement.

2. THEORETICAL BACKGROUND

The spectroscopic properties of the wide range of rare earth materials used in the sensors considered have been discussed have been discussed in several previous papers by the authors [14][15][21] and are considered in some detail by Digonnet [22]. The background to the fluorescent decay time approach, which has been used in this work for temperature and strain monitoring, has been discussed in detail in our previous work [3]. This intensity-independent method offers a relatively simple method to determine temperature change.

Thermal effects and physical strain can be separated in an optical fiber sensor system to enable these individual measurands readily to be obtained. An ideal sensor system from which two measurand-dependent observables, τ and λ, e.g. the fluorescence lifetime produced by the rare-earth doped fiber and the wavelength reflected by the fibre Bragg grating written in the fibre, at a certain temperature T and a specific strain ε may be considered. In practice, both observables each show some sensitivity to both ε and T [1], so that

$$\begin{bmatrix} \tau \\ \lambda \end{bmatrix} = \begin{bmatrix} K_{1T} & K_{1\varepsilon} \\ K_{2T} & K_{2\varepsilon} \end{bmatrix} \begin{bmatrix} T \\ \varepsilon \end{bmatrix} \qquad (1)$$

such that

$$\begin{bmatrix} T \\ \varepsilon \end{bmatrix} = \frac{1}{K_{1T}K_{2\varepsilon} - K_{2T}K_{1\varepsilon}} \begin{bmatrix} K_{2\varepsilon} & -K_{1\varepsilon} \\ -K_{2T} & K_{1T} \end{bmatrix} \begin{bmatrix} \tau \\ \lambda \end{bmatrix} \qquad (2)$$

That is, the simultaneous measurement of strain and temperature by using two sensing elements is possible with a knowledge of the calibration parameters of the system. The temperature and strain errors arising from the above system may be estimated respectively below as:

$$|\delta T| = \frac{|K_{2\varepsilon}||\Delta\tau| + |K_{1\varepsilon}||\Delta\lambda|}{|K_{1T}K_{2\varepsilon} - K_{2T}K_{1\varepsilon}|} \qquad (3)$$

$$|\delta\varepsilon| = \frac{|K_{2T}||\Delta\tau| + |K_{1T}||\Delta\lambda|}{|K_{1T}K_{2\varepsilon} - K_{2T}K_{1\varepsilon}|}$$

A particular description of the simultaneous discrimination of temperature and strain based on the use of dual elements, for example, one doped fiber combined with grating, is possible in terms of Eqs. (1) and (2) with the error tolerance being estimated from Eqs.(3) and (4), above.

3. EXPERIMENTAL ARRANGEMENT

The thermal behaviour of the fibres under study has been demonstrated in this work by using the experimental arrangement shown in Figure1, which is similar to that used for the rare-earth ion doped fibres tested before by the authors [13]. Typically, a laser diode, with an appropriate centre wavelength, is employed as the optical source, chosen so that light may couple readily to the broadened absorption band of the doped material. The fibre under study was placed within the optimum thermal region to experience a stable temperature in the tube oven used (10cm for the CARBOLITE type: MTF 12.38/400, the central temperature of which is within at least ±5°C of that indicated and considerably better on average over the period during which the results are taken). The fibre element used was fusion-spliced to the sensor arm of a 2×1 optical fiber coupler (to separate source light and fluorescence and used to transmit the excitation light to the sensing probe, and to collect the resulting fluorescence response received from the sensor element). This bare-fibre sensor element was placed loosely in a quartz tube and centered in the stable oven. An infra-red sensitive, typically an InGaAs photodiode was used to detect the fluorescence emission and the signal was transmitted to a computer via an analog-to-digital (A/D) card attached to it, for further processing by using Prony's method, as discussed previously [23], to obtain the temperature dependent fluorescence lifetime data.

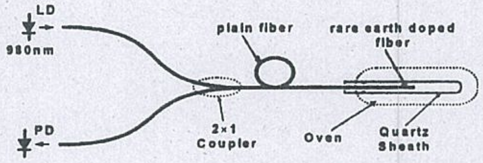


Figure 1 Experimental arrangement for the measurement of fluorescence characteristics of the rare earth doped fibre samples.

It is clearly important for a worthwhile sensor in any practical application that a stable and reproducible response is seen. Earlier studies on rare earth doped fibres had shown that a significant and apparently irreversible change in the fluorescence characteristic does occur if the doped fiber has been exposed to high temperatures, above a certain point. In order to enable the probe to possess a consistent and stable thermal characteristic, an "annealing" process was recommended and implemented, requiring pre-treatment of the fiber at high temperatures.

A similar experimental arrangement has been used for the fibre Bragg grating thermal tests, with the difference being the laser diode and the photo-detector shown in figure 1 are replaced by a broadband LED and an optical spectrum analyser (OSA), respectively.

The experimental arrangement used for the measurement of the strain-induced fluorescence characteristics of several fibres over a range of temperatures up to 150°C is illustrated in Figure 2. This is very similar to the arrangement for temperature monitoring alone, and incorporating into it a tube oven to provide local heating of the fibre, both strain and temperature excursions can be applied. When the doped fiber was stretched by using a calibrated constant weight and kept at a stabilized temperature, the PLD monitoring system discussed previously [24] is accurate enough to keep the fluctuation of the sampled lifetime data within ± 0.05μs, which excludes other possibilities for a lifetime variation than that due to the strain imposed (within the quoted oven sensitivity), to observe the phenomenon observed in the strain sensitivity test. For the multimode fiber, a strain level of up to 1400με has typically been applied and tests carried out over a range of temperatures, whilst for the single-mode fibre, a limit of 600με has been set, due to its different physical properties. These values are chosen to be below the experimentally observed strain which causes fibre fracture, and represent extensions of > 1% and just less than 1% respectively. Fibre fracture was observed at ~2.4% extension (~2400με in the multimode fibre test at room temperature).

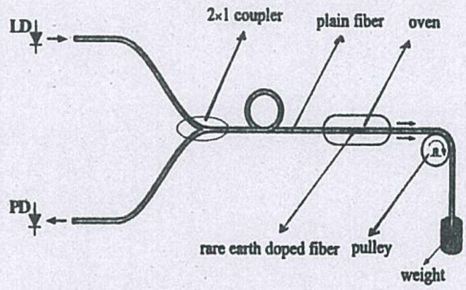


Figure 2 Simplified schematic of the experimental arrangement for the strain testing of rare earth doped fibres.

4. EXPERIMENTAL RESULTS

In this section, typical results from a range of fibres under test for sensor applications are discussed and compared.

4.1 Ytterbium (Yb) – doped fibre characteristics

Ytterbium doped fibres offer a wide range of applications as fiber lasers and amplifiers [21][25], and their ability to provide amplification over the very broad wavelength range from ~975nm to ~1200nm is expected to generate increasing interest in the near future [26]. Apart from their broad-gain bandwidth, Yb-doped fiber used in amplifiers can offer high output power and excellent power conversion efficiency [27].

Two types of single mode Yb^{3+} doped silica fibers were put under test, termed here YbH and YbL (the final letter of the code refers to high, medium and low doping, as defined below, respectively). The fibers were manufactured by INO, Canada, where the diameter of YbL sample was 3.4μ m/125μm (core/cladding), while that of YbH was 2.8μm/124μm. The dopant concentration of YbH is Yb: 2.5wt%, Al: 8.3wt%, Ge: 0.5wt% and YbL is Yb: 550ppm-wt, Al: 2400ppm-wt. The fluorescence decay signal recorded for each sample, at a chosen stabilized temperature, is shown in Figure3, normalized to their respective initial intensity levels. These graphs clearly show that the decay is single exponential regardless of the level of dopant concentration.

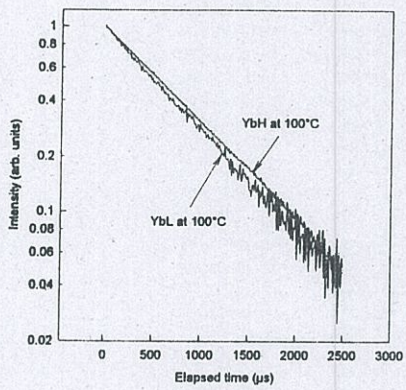


Figure 3 Fluorescence signals as a function of time at the temperature of 100°C.

4.2 Er (+Yb) – doped fibres

(a) Thermal characteristics

In order to test the characteristics of the co-doped fiber which has been annealed as a temperature sensor, several thermal cycles ranging in temperature from 20°C to 850°C have been carried out and the calibration graph of the lifetime during a series of thermal cycles from 20°C to 850° C, taken after the annealing process, is presented in Figure4. This corresponds to the practical situation for any thermal sensor of this type. In this case deviations of these data from the average regression fit are depicted in the upper graph of the figure. They are within the region equivalent to changes of ±5°C in temperature, which correlates well with the temperature stability of the oven used and they show no significant indication of hysteresis in the lifetime measurements. This is very positive result for their use in fiber optic fluorescence thermometry. In addition, when comparing with the performance under annealing tests with that of other rare-earth doped fibers, such as Nd^{3+} [12], Er^{3+} [13][14], Yb^{3+} [15] and Tm^{3+} [16], the Yb/Er co-doped fiber has a much lower lifetime drift due to the thermal annealing and this is a valuable feature of the performance of this fibre.

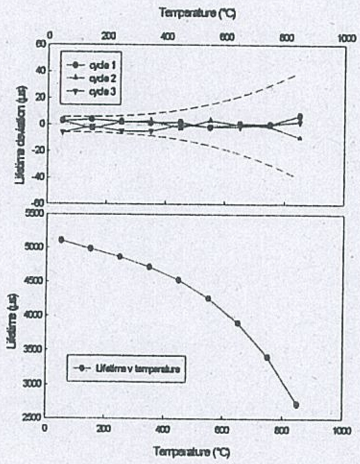


Figure 4 Thermal cycle graphs of fluorescence lifetimes of a sample of Er/Yb fibre after being annealed.

(b) Reflectivity of the fibre Bragg grating written in Er/Yb co-doped fibre.

A similar setup has been used for the thermal tests on the FBGs shown in Figure 5 where the co-doped fibre was of unique construction in that it had been designed with a photosensitive ring (during the manufacturing process), and the grating was written into it, using a frequency-doubled argon ion laser (244nm), without requiring prior hydrogen loading of the fibre. This fiber had a diameter of 125 μm, a numerical aperture of 0.2 and core dopants of Er^{3+}, Yb^{3+} and aluminium.

The reflectance characteristics of the FBG written in the Er/Yb co-doped fibre was shown in Figure 6, when it was subjected to the long term high temperature environment produced by the oven. At each specific temperature, the reflectance tended to drop dramatically at the start, but gradually stabilized and the FBG ceased to function at 400°C, after the grating has been exposed to a high temperature for nearly 1300 hours. Similar results have been produced for normal grating written in photosensitive fibres by using a pulsed excimer laser at 248 nm, and these will be shown below.

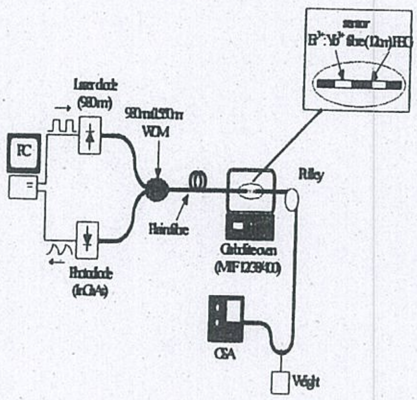


Figure 5 Thermal tests of the sensor with FBG written in Er/Yb co-doped fibre.

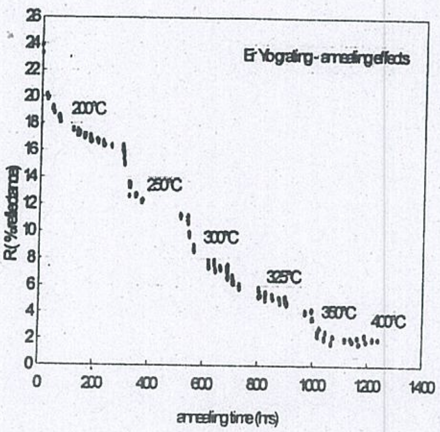
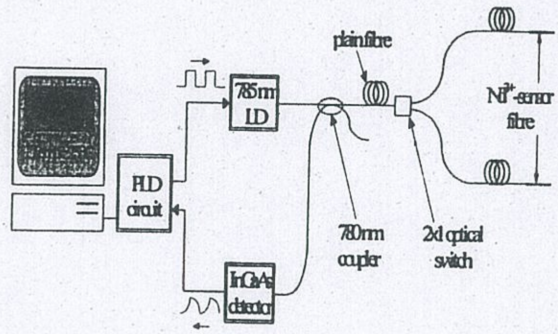


Figure 6 Long term annealing effects on the FBG written in Er/Yb co-doped fibre.

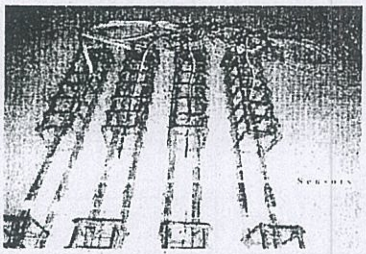
4.3 Nd-doped fibre characteristics

(a) Probe tests in structural integrity applications.

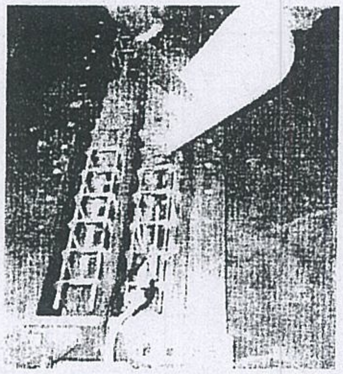
This sensor scheme is well suited to structural monitoring ('smart sensor') applications and using Nd doped fibre, in a system which is shown in Figure 7 (a). Excitation of the Nd-doped fibre was from a ~20 mW laser diode at 785nm, via a 3dB optical fibre coupler and 2×1 optical switch. An optical switch was incorporated into the design to test the ability to multiplex several temperature probes with a single excitation and detection system. The fluorescence signal from the sensor probes was monitored using an InGaAs detector, the output of which was coupled to the PLD system [22]. Software has been developed to record the lifetime of the active fluorescent element of the fibre probes and to convert the measurements to a temperature using calibrations of the lifetime versus temperature dependence. Figure 7 (b) and (c) shows that several samples of temperature sensing probes being installed in concrete beams in tests in that environment.



(a)



(b)



(c)

Figure 7 (a) Setup of the structural integrity monitoring system; (b)-(c) Installation of optical fibre temperature sensing probes in concrete specimens.

In order to study reproducibility of such systems, eight different probes have been fabricated and tested. The lengths of the Nd doped fibres used in these probes were between 2 and 6 cm over this range of probes. Figure 8 shows their corresponding lifetime versus temperature characteristics of a typical probe when the test oven temperature varies from room temperature to 305°C. Comparison is also made with 2 K-type thermocouples co-located in the structure, the results of which are also shown in the figure. The data obtained show how effective the system is for such measurements over this range.

(b) Strain monitoring using Nd-doped fibre
At a range of stabilized temperatures, these being room temperature (~20°C), 60°C, 100°C and 150°C, a series of strain response tests was performed. To do so, weights were applied and the magnitude of the weight used with the multimode Nd doped fiber was increased, step by step, giving increments corresponding to ~200με to ensure that the strain on the doped fiber moved up gradually and progressively from 0 to 1400με. this strain is calculated from the physical parameters of the fibre). The corresponding fluorescence lifetimes were monitored as a function of converted strain and are presented in Figure9. Results are shown for each temperature and for strain applied ('strain up') and strain removed ('strain down') (i.e. one 'roundtrip') to investigate if any hysteresis occurred and was observed.

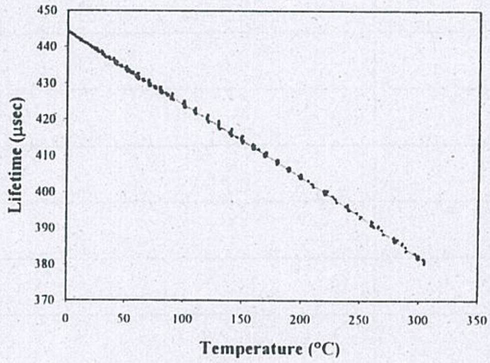


Figure 8 Lifetime versus temperature characteristics for 8 different Nd-doped fibre probes.

The results show that with increase of temperature, the lifetime of the fluorescence generated by the doped fiber decreases dramatically compared with the strain-induced lifetime variations, the temperature characteristic of which has been discussed in detail elsewhere by some of the authors [10] [12]. At each stabilized temperature also shown in Figure9, the lifetime of the fluorescence signal observed from the multimode Nd doped fiber increases quite linearly with increasing strain, where the rate of the variation is approximately $5(\pm 0.5)\times 10^{-4}$ μs/με and the lifetime variation induced by the maximum applied strain (1400με is equivalent to the lifetime change caused by a temperature variation of about 2.5°C. Similar results have been reported by Shen et al in experiments on the application of pressure to bulk Cr^{3+}:YAG [28] samples.

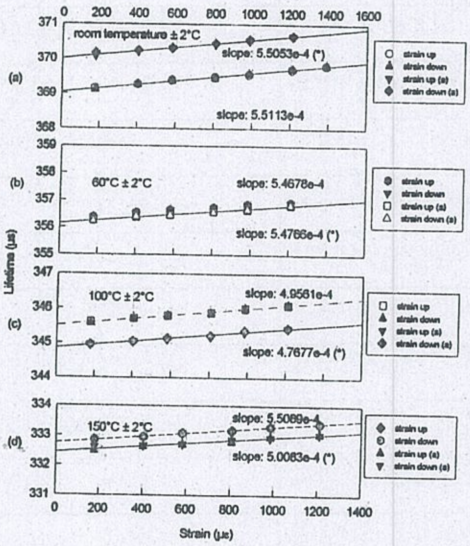


Figure 9 Lifetime variation of multimode Nd-doped fibre as a function of strain over a range of temperatures before and after stress annealing (graphs marked with *) showingthe strain sensitivity of the fluorescence lifetime keeps almost constant regardless of the variation of temperature and strain. (a)-(d) Temperatures are room temperature, 60, 100, 150°C, respectively (± 2°C in each case).

4.4 Tm-fibre based fire alarm system

A simple yet effective means has been used to determine the presence of a small temperature excursion (evidenced by a local change in the decay time of the fluorescent species so influenced) against a background of sensing the ambient temperature. The aim is for applications in alarm sensing where the heat of a fire causes a localized temperature excursion in the fiber. To monitor this using the time domain is relatively difficult and prone to error - the frequency domain approach is applied to offer a potentially simpler signal processing solution [29]. To do so, pulsed excitation is used but only the decay signal, observed when the pump power was switched off, is monitored which obviates the problem encountered with leakage of the excitation light. Thulium doped fibre has been tested due to its short lifetime, which produces a rapid response and the configuration of the system is shown in Figure 10.

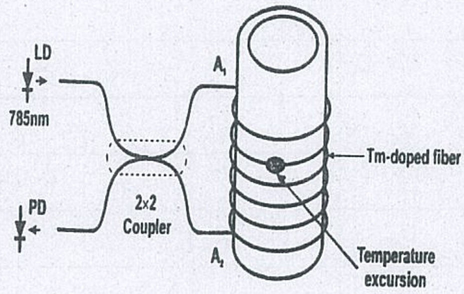


Figure 10 Configuration for fire alarm system using Tm doped fibres.

To overcome the long term drift caused by the electrical circuits and temperature fluctuation, a differential scheme has been used [29] by the authors to determine most effectively the hot spot in the sensing loop. Figure 11 indicates clearly the occurrence of hot spot when various sections of the sensing loop tested is exposed to temperature excursions to simulate this.

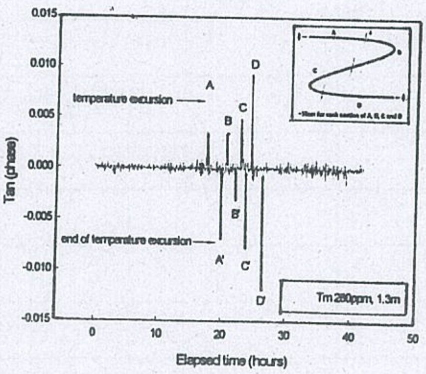


Figure 11 Hot spot pick up by using differential phase shift method.

4.5 Thermal characteristics of FBGs written in photosensitive fibres

Further to the investigation on FBGs written in Er/Yb co-doped fibre (kindly supplied by Nanyang Technological University of Singapore), the authors have used an excimer laser (Lambda Physik laser) for the purpose of writing FBGs. The setup was shown in Figure 12, where the pulse power of the excimer laser was adjusted to 18 mJ and the repetition rate to 15Hz. The photosensitive fibre used here was supplied by Fibercore Ltd., the core of which is boron-germanium co-doped and the fibre was exposed to the UV beam for 30 seconds. The reflection spectra of the FBG, when subjected to different temperatures, shown in Figure 13 where the higher temperature has reduced the reflectivity and shifted the peak wavelength of the grating. Figure 14 is the result of long term thermal stability tests on the grating and similar results to those shown previously from the FBG in Er/Yb co-doped fibres have been produced.

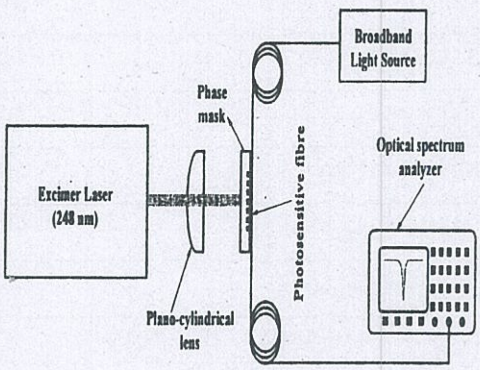


Figure 12 Experimental setup for FBG written.

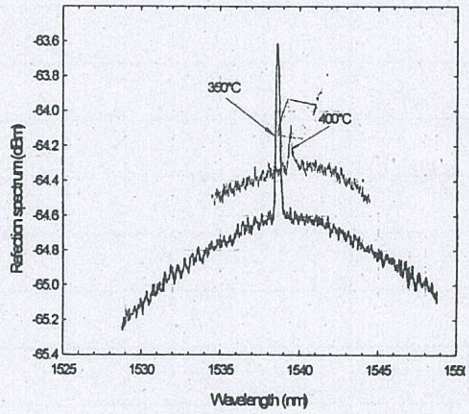


Figure 13 Reflection spectrum of the FBG fabricated by using a pulsed excimer laser.

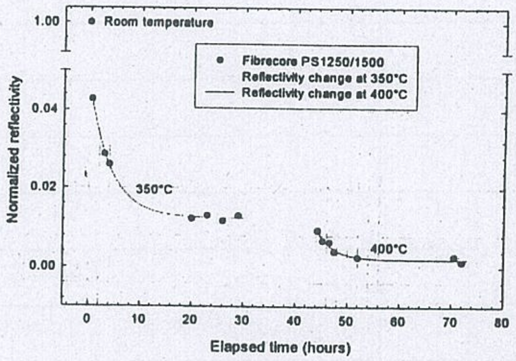


Figure 14 Long term thermal stability tests of the FBG written in photosensitive fibres.

5. SUMMARY

A series of readily available rare earth doped fibres has been reviewed in this paper for their potential use as the key element of several different fluorescence based sensor systems operating over a wide temperature range and in some cases their strain sensitivities have been considered. Overall the results obtained from these doped fibres look promising for the development of effective, compact and intrinsic fibre temperature probes. The industry-linked research into both a structural integrity monitoring system and fire alarm system by using rare earth doped fibres mentioned above has confirmed the valuable applications of these optical fibre based sensors, which potentially offer better performance than conventional sensors in some hostile environments. In addition to the investigation on the temperature characteristics of rare earth doped fibres which was carried out, the strain sensitivity of the fibres has also been investigated. The incorporation of FBGs in doped fibres or photosensitive fibres has enhanced the possibility for wide range of strain and temperature measurement and the on-going research on the thermal stability of FBGs will enable the extension of the sensing range for potential applications in the oil and steel industries.

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