Temperature monitoring of vehicle engine exhaust gases under vibration condition using optical fibre temperature sensor systems

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Abstract. Two optical approaches, comprising and contracting both the fluorescence decay lifetime and the fibre Bragg grating (FBG) methods, were developed and evaluated for temperature monitoring of exhaust gases for use on a vehicle engine. The FBGs used in the system were written into specially designed Bi-Ge co-doped photosensitive fibres, to enable them to sustain high temperatures to over 800°C, which is far beyond that of FBGs written into most commercial photosensitive fibres. The sensors were subjected to a range of vibration tests, as a part of an optical exhaust monitoring network under development, and results from the test carried out are reported.

1. Introduction

Exhaust emissions from cars, trucks and other road vehicles produce a major source of air pollution[^1]. The increasing traffic volume produces a high level of species, such as CO, NO\(_x\), HC and SO\(_x\), in the urban environment, which affect the health of human beings and animals. Hobbs notes that more than one-third of the carbon in vehicular emissions is now the highly poisonous gas, CO[^2]. Diseases of the respiratory system such as bronchitis or pulmonary emphysema are generally correlated with the level of CO present[^3]. Thus it has become vital to keep pollutant emissions to a minimum. Using emission control technology is a practical way to do this, involving reliable, robust and cost effective means of monitoring the pollutant and containment levels in the exhaust systems.

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The main pollutants, CO, NOx, HC and SOx, can be monitored through the measurement of the absorption light from specific pollutant gases in the vehicle exhaust system. It is also important to measure the temperature of the exhaust gases, as the optical absorption of the various species is temperature dependent, and for control of the engine operational conditions.

Vehicle emissions can be hostile, with hot corrosive gases being present. In addition, electromagnetic interference (EMI) in vehicles is a growing problem in sensor design for the range of measurements required. For example, the use of a new microwave powered catalytic converter, under development, may result in the presence of an intense localised electromagnetic field in the vehicle engine.[4] In general, the major requirements for exhaust gas monitoring are:

- High temperature operation range: The temperature of the exhaust gas could reach some 600°C
- Insensitivity to mechanical vibration: The exhaust systems in road vehicles encounter considerable shaking and bumping. The mechanical forces exerted on any sensor mounted on the exhaust system are therefore considerable.
- Insensitivity to chemical corrosion: The combined heat and water contents of exhaust emissions result in a highly corrosive mixture, which would result in damage to many conventional sensors.
- Immunity to EMI. The intense electric fields present in the vehicle, may interfere with the operation of conventional electronic sensors.

In this case, optical sensor systems offer a viable approach to monitor gas species and temperatures in the exhaust, as they can be miniaturized, and made robust and immune to the above effects.

During the last decade, many optical fibre sensor systems have moved from the laboratory to industry, evidenced by a number of reports on applications of advanced optical fibre sensor systems developed for specific situations.[5,6] In response to the above, this paper reports on a novel application of two optical fibre temperature sensor systems, using fluorescence-based and FBG-based temperature sensor systems, in monitoring the dynamic temperature changes of the exhaust gases from a vehicle engine, experiencing vibration conditions in use. The work forms part of a research project on the monitoring of vehicle emission under operational conditions by optical methods.

The optical temperature sensor systems considered in this work can readily be integrated with other optical probes for exhaust gas measurement in building an intelligence emission monitoring system for vehicles. Figure 1 shows a schematic set up of an integrated vehicle exhaust gas monitoring system. Such an optical system can also offer the advantage that the probe can be located at any point along the exhaust system, e.g. immediately following the catalytic converter, where such measurements are particularly important.

2. Optical Sensor Schemes

Two different optically-based temperature sensor schemes were developed and evaluated in this work, to meet the requirements of temperature measurement of the application.

![Figure 1. Configuration of an optical sensor network for vehicle exhaust gases measurement](image-url)
2.1. Fluorescence-based temperature sensor system

This fibre optical sensor scheme, using a fluorescence-based approach is based upon previous research by some of the authors. The temperature is obtained through monitoring of the fluorescence decay time of a rare earth material, which is temperature dependent \(^{(7)}\). The system setup is shown in Figure 2(a), with the probe design illustrated in Figure 2(b). The fluorescent medium used, thulium-doped garnet (Tm: YAG) crystal, was used over a well defined temperature range (up to 1100°C). It is excited by light from a Laser Diode (LD) light source operating at 785 nm coupled to the active material through a silica fibre Y-shaped bundle. The fluorescence emission received is detected with an extended wavelength InGaAs photodiode, which covers the spectral range of 900nm to 2200nm, and the lifetime data are extracted using a phase locked detection (PLD) scheme, following which the temperature value is derived from prior calibration \(^{(7,8)}\).

This system operates over the high temperature range from room temperature up to 900°C, and this can be increased to 1100°C by applying black body radiation compensation technology \(^{(9)}\). It typically has a temperature precision of about ±2°C over the temperature range of 25–800°C, determined by a laboratory comparison with the output of a thermocouple, without being subjected to external vibration. Figure 3 shows the fluorescence lifetime of the Tm: YAG crystal under different temperatures.

\[ T \text{ (°C)} \quad 0 \quad 200 \quad 400 \quad 600 \quad 800 \]
\[ \text{Lifetime (us)} \quad 1000 \quad 2000 \quad 3000 \quad 4000 \quad 5000 \quad 6000 \quad 7000 \quad 8000 \]

**Figure 2.** Fluorescence-based Optical fibre temperature sensor.
(a) system design (b) optical probe design

**Figure 3.** Fluorescence lifetime versus temperature characteristics of Tm:YAG crystal

2.2. A FBG-based temperature sensor system.

The FBG-based temperature sensor system has been widely used for a range of sensor applications \(^{(10,11)}\). In this work, a portable FBG-based temperature sensor system was built and evaluated, and is shown schematically in Figure 4, using a Fabry-Perot tunable filter for FBG wavelength detection. A user-friendly interface for the system was programmed using a LabView platform. A print-out of the interface software is illustrated in Figure 5.

![Diagram](image)

The conventional type I or type IIA FBGs, written into some commercial photosensitive fibres, such as Ge doped fibre and B-Ge co-doped fibre, would be erased if the FBGs were subjected to high temperatures as high as 500°C \(^{(12)}\). Such temperature characteristics of the conventional FBGs do not satisfy the requirements of several high temperature applications. A special feature of the sensor system here is that the FBGs used in this work were written into a Bi-Ge co-doped photosensitive fibre, which is developed for high temperature applications by some of the authors. The specially designed fibre was fabricated by the means of the modified chemical vapor deposition (MCVD) method detailed in prior...
work \cite{13}, with the doping concentrations of 5000 ppm of Bi$_2$O$_3$ and 15 wt% of GeO$_2$. Strong FBGs were written into the Bi-Ge co-doped fibre by exposing the photosensitive fibre to UV emission from a KrF excimer laser at 248nm through a phase mask. The FBGs obtained can sustain a temperature of over 800°C, and this opens up the potential of FBG-based systems for reliable high temperature monitoring.

The temperature characteristics of the FBG written into the Bi-Ge co-doped fibre were tested by annealing the FBGs at 500°C, then at 800°C for several days, and the results are illustrated in Figure 6. The initial reflectivity of the FBG tested is 97%, and it dropped to 89% after the annealing temperature rose from room temperature to 500°C in around 40 minutes. After being annealed at 500°C for 144 hours, the remaining reflectivity level was 79%. Following that the annealing temperature was increased to 800°C, resulting in a reflectivity drop to 23%. The final reflectivity level was 2%, after annealing at 800°C for 50 hours. This test clearly shows that the strong FBGs written into the Bi-Ge co-doped fibre can sustain high temperatures of over 800°C. The wavelengths of the FBG under different temperatures were also measured, and shown in Figure 7, which illustrates that it has a temperature sensitivity of about 12pm/°C in the range from room temperature to 1150°C, with little non-linearity, similar to the behavior of FBGs written into Ge-dope photosensitive fibres \cite{14}. The FBG was placed loosely (for the resultant strain effect on the FBG to be negligible) into a ceramic tube with a diameter of 1.5mm and a length of 200mm to form a temperature probe.

Before being used for temperature monitoring under vibration conditions, this FBG-based sensor system was carefully calibrated in the laboratory, showing a temperature precision of typically ±2°C. These specifications meet the requirements of the project for temperature monitoring of vehicle engines.

**Figure 4.** Schematic view of the FBG-based temperature sensor system

**Figure 5.** Printout of the interface for the FBG-based temperature sensor system
3. Temperature monitoring under vibration conditions

The above two optical temperature sensor systems were used to monitor the temperatures of the exhaust gases of a vehicle engine in experiments carried out at the University of Liverpool. Both the optical probes, i.e. the fluorescence probe and the FBG probe, were fixed within the exhaust pipe of the engine, as shown in Figure 8. A thermocouple was also placed in intimate contact with the optical probes to enable a comparison with the readings from the optical sensors to be made.

A series of tests was carried out under different vibration conditions, by controlling the different engine condition, i.e. the engine running at a constant speed, a regularly changing speed and a randomly changing speed respectively. Figure 9 shows the results obtained from the tests carried out under the highest...
vibration condition of the engine, and Figure 10 shows the results obtained while the vibration was being changed randomly by changing the operation speed of the engine for 20 minutes.

The results show that the measurement precision of the fluorescence-based sensor for a ‘spot’ measurement was dramatically decreased to ±15°C, from ±2°C under conditions of no vibration. The main reason for this performance degradation is that the intensity of the optical signal was affected by the vibration applied on the probe structure and the resultant change in the optical intensity received, thereby affected the performance of the phase-locked detection scheme. Work is currently being undertaken to tackle this problem by redesigning the probe and the signal processing scheme, as this is not a problem that is fundamental to the method of measurement.

As shown below, by contrast, the results obtained by using the FBG-based temperature sensor system show that the sensor had a precision of about ±2°C, giving a result which was the same as that for the measurement carried out under laboratory conditions with no vibration. This scheme takes advantage of the fact that the FBG sensor system is based on wavelength modulation rather than intensity modulation, and it is an in-fibre sensor, less sensitive to environmental disturbances when the probe is well designed.

4. Discussion
Two optical fibre sensor systems, as discussed above, have been designed for monitoring the temperatures of the exhaust gases from a vehicle engine. By using different engine speeds, these sensor systems have been tested and evaluated under different vibration conditions. The results show that the FBG-based sensor system was not affected by the vibration applied in the tests, and thus proved to be well suited to this kind of application. However, the fluorescence-based sensor system was affected significantly by the vibration, and requires a redesign for the applications. Furthermore, the strong FBGs, written into a specially designed Bi-Ge co-doped photosensitive fibre, which can sustain high temperatures over 800°C, have opened up the potential for high temperature applications of FBG-based sensors for this use. Further work is being carried out to combine these optical temperature sensors with other optical gas sensors for effective vehicle emission measurement and control.

![Figure 9. Temperature monitoring of a vehicle engine exhaust under highest vibration condition for 1 hours](image)

(a) fluorescence-based sensor (b) FBG-based sensor
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