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Optical fibre temperature sensor in the cryogenic range

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The realization of an optical fibre sensor applied to cryogenic temperature measurement in harsh environments is presented. The measurement principle is based on the analysis of the decay-time of the fluorescence emitted by special doped crystals, the excited state lifetimes of which are greatly dependent on temperature. The sensor is intended to work in the presence of strong perturbations encountered on the testing benches of the liquid hydrogen and liquid oxygen turbo-pumps of the Ariane 5 Vulcan engine developed by 'la Societé Européenne de Propulsion (SEP)'. Copyright © 1996 Elsevier Science Ltd.

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Introduction

Special needs for temperature control and regulation in harsh environments have given rise to the development of optical sensors resistant to such environments. Extrinsic sensors, where the optical fibre is used only as a transmission support, are well suited to severe surroundings, especially the fibre optic fluorescence techniques—most of which are collected and described by Grattan and Zhang[1]. One of the most prevalent methods is the analysis of the decay-time of the fluorescence emitted by doped crystals. This method leads to precise results with a good level of reproduction. The principle of the measurement with luminescent crystals is quite simple: under a photonic excitation pulse, the crystals emit a fluorescent signal with a temporal decrease greatly dependent on temperature. A lot of crystals are available to cover a large temperature range[2,3].

In the cryogenic domain in which we are involved, calcium fluoride doped with divalent ytterbium ($CaF_2:Yb^{2+}$) and strontium fluoride doped with divalent ytterbium ($SrF_2:Yb^{2+}$) have a great sensitivity to temperature in the range 20 K–120 K, which corresponds to liquid hydrogen and liquid oxygen temperatures. These two crystals constitute the sensitive part of the measurement probes, realized to withstand space norms such as thermal and mechanical strains (vibrations, high pressure, high speed flows) and have a good chemical compatibility with oxygen and hydrogen[4]. The probes were tested on a liquid hydrogen turbo-pump at SEP. The tests showed a good resistance of the probes to thermal and mechanical strains as well as the good behaviour of the whole prototype sensor.

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Luminescent crystal properties

The temperature measurement is based on the analysis of the fluorescence decay-time. Its strong dependence with respect to temperature is favourable for measurement precision. $CaF_2:Yb^{2+}$ and $SrF_2:Yb^{2+}$ crystals have a two-excited-states electronic structure. The lower state is metastable (that is, its transitions with the ground state are forbidden), and the upper state is the emitter state[5,6]. These two states are in thermal equilibrium within the temperature range 20 K–120 K. Therefore, the time the electrons stay on the metastable state, in other words the fluorescent decay-time, varies greatly with the energy induced by thermal excitement in this cryogenic range (20 K–120 K). In a spectroscopic point of view, the absorption spectra at the low temperature of $CaF_2:Yb^{2+}$ and $SrF_2:Yb^{2+}$, show a high absorption band around 28 500 cm^{-1} ($\lambda \approx 350$ nm) (see Fig. 1)[6,7]. When they are excited in this ultraviolet absorption band, the crystals emit fluorescent light centred on the yellow wavelength ($\lambda \approx 560$ nm) for $CaF_2:Yb^{2+}$ and the near-infrared ($\lambda \approx 800$ nm) for $SrF_2:Yb^{2+}$ (see Fig. 2)[6].

Basic principle of the measurement

In response to a short duration ultraviolet excitation pulse, $CaF_2:Yb^{2+}$ and $SrF_2:Yb^{2+}$ crystals emit a fluorescent signal with a temporal decrease following the law

$$I = A_0 e^{-t/\tau_f} + B_0 e^{-t/\tau_s} \quad (1)$$

where τ_f is a fast component of the excited state lifetime and τ_s is a slow one. In the low temperature range,

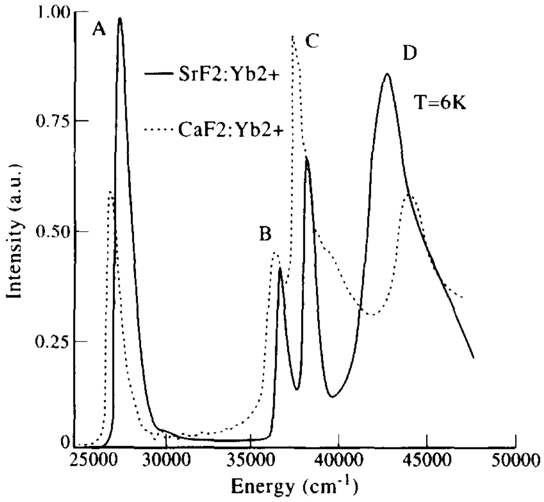

Fig. 1 $CaF_2:Yb^{2+}$ and $SrF_2:Yb^{2+}$ absorption spectra at $T = 6$ K

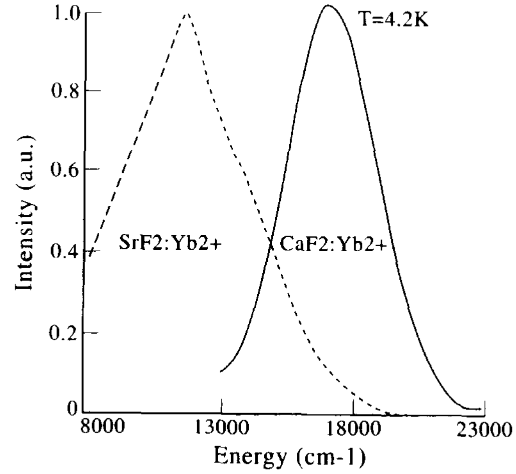

Fig. 2 Emission spectra at $T = 4.2$ K of $CaF_2:Yb^{2+}$ and $SrF_2:Yb^{2+}$ crystals excited at $\lambda = 355$ nm

where radiationless processes are negligible, the lifetime is equal to τ_s. Moreover, τ_f is too fast to be easily detected experimentally[5,6]. So we assume that the fluorescence signal decrease is given by the law

$$I = I_0 e^{-t/\tau} \tag{2}$$

where I_0 is the fluorescence intensity at the initial time and $\tau = \tau_s$ is the excited state lifetime greatly dependent on temperature[5,6]. To calculate τ, we apply a logarithmic regression to the fluorescent signal. We then obtain a straight line whose equation is $y = ax + b$, where the slope value, a, equals $-1/\tau$ (see Figs 3(a) and (b)). This calculation was applied to signals issued from $CaF_2:Yb^{2+}$ and $SrF_2:Yb^{2+}$ crystals, to define their working range:

(1) $SrF_2:Yb^{2+}$ crystal is better suited to low temperatures (from 20 K to 80 K) with a decay-time varying from 10 μs at 80 K to 120 μs at 20 K;
(2) $CaF_2:Yb^{2+}$ crystal can cover the whole temperature range with a decay-time from 180 μs at 120 K to 1100 μs at 20 K. However, its fluorescence efficiency is significantly higher between 80 K and 120 K.

These two crystals are therefore perfectly complementary in the temperature range 20 K–120 K. Between two consecutive excitation pulses, we have to wait for five times the decay-time value. Accordingly, temperature can be measured with a repetition rate ranging from 140 Hz to 20 kHz. It depends on the crystal used and the temperature range.

Optical probe characteristics

To measure temperature, we need two operations:

(i) luminescent crystal excitation by a short duration ultraviolet pulse;
(ii) fluorescent signal detection and processing.

The optical probe architecture is simple. It consists of a luminescent crystal, bonded at the extremity of a unique multimode optical fibre, guiding the ultraviolet beam towards the crystal and the fluorescence beam coming from the crystal. It is important to notice that the probes are conceived to be implemented on the cryogenic turbo-pumps of the Vulcan engine, which introduce very strong perturbations such as:

- thermal strain: 20 K–120 K;
- cryogenic fluids high pressure: 200 atm;
- high speed flow of these fluids: from 100 m s^{-1} to 300 m s^{-1};
- mechanical vibrations;
- chemical compatibility of materials with hydrogen and oxygen.

It is therefore necessary to elaborate a mechanical system to protect the luminescent crystal affixed to the

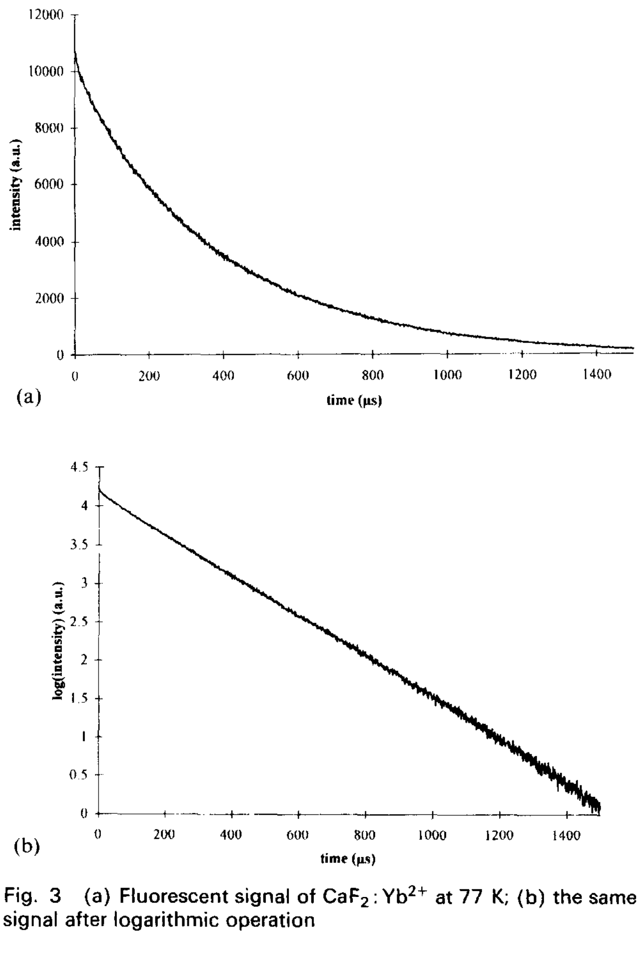

Fig. 3 (a) Fluorescent signal of $CaF_2:Yb^{2+}$ at 77 K; (b) the same signal after logarithmic operation

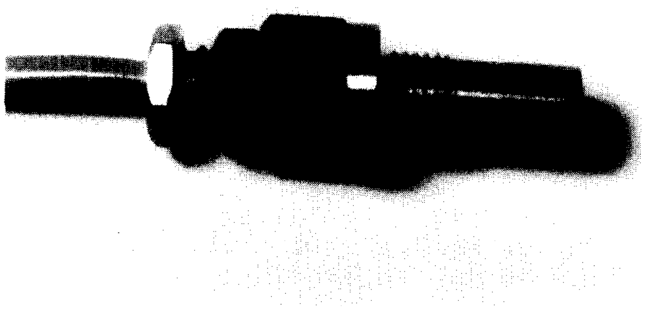

Fig. 4 Photograph of a probe

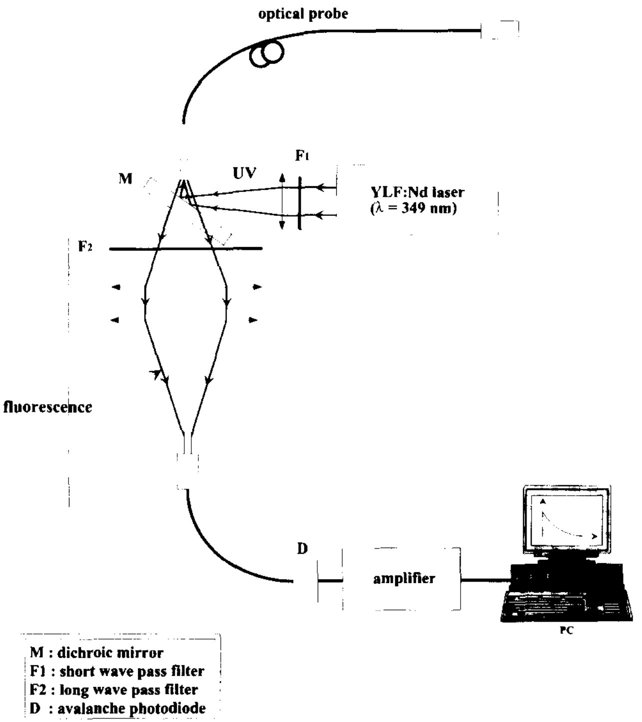

Fig. 5 Experimental set-up of the cryogenic temperature sensor by photoluminescence

optical fibre with a special glue, having a low ultraviolet absorption coefficient and a good resistance to cryogenic and vibratory environments. To validate the choice of material and the probe concept, each of the strains previously listed was reproduced in specialized laboratories and applied to prototype probes. These laboratory tests led to the concept of a metallic capsule to protect the luminescent crystal as well as a mechanical interface for the implementation of the probes on the turbo-pumps (see Fig. 4).

Experimental set-up and results

The set-up scheme is presented in Fig. 5. The luminescent crystal is excited with a pulsed Nd : YLF frequency tripled laser ($\lambda = 349$ nm) emitting 70 μJ energy pulses with 5 ns duration. The dichroic mirror is an essential component which divides excitation and fluorescence beams. The fluorescence is detected by an avalanche photodiode. To achieve a good precision on the temperature measurement under the working conditions of the turbo-pumps, the analogue signal issued from the photodiode has to be sampled at 1 MHz frequency and stored in a computer via a 14 bits acquisition board. The fluorescence decay-time value is calculated from this digitized signal and the corresponding temperature is then given by calibration curves stored beforehand.

For the calibration operation, the probes are placed in a liquid helium cryostat and the fluorescence decay-time is calculated for each temperature measured by a reference electric sensor located in the vicinity of the optical probes. The calibration curves are presented in Figs 6 and 7. To determine temperatures from these curves, we develop a theoretical model from the experimental points. It is an n-order polynomial fitting, i.e.

$$T = a_0 + a_1\tau + \ldots + a_n\tau^{n-1} \quad (3)$$

where T is the temperature and τ the fluorescence decay-time. The performances of the sensor were estimated first in a static environment without any perturbations and then in actual working conditions of the turbo-pumps. In each case, temperature was calculated ten times per second to follow in quasi-real time the thermal evolution of the cryogenic fluids, especially when the turbo-pumps fired. That repetition-rate is largely sufficient because the time-response of the probe is actually estimated at 1 s. The precision of the measurement given below, corresponds to the standard deviation around the mean value calculated from 50 signal acquisitions for a given temperature value. In the static environment, temperature was measured with a precision of ± 0.1 K in the best case ($SrF_2 : Yb^{2+}$ between 20 K and 60 K), and ± 0.4 K in the worst one

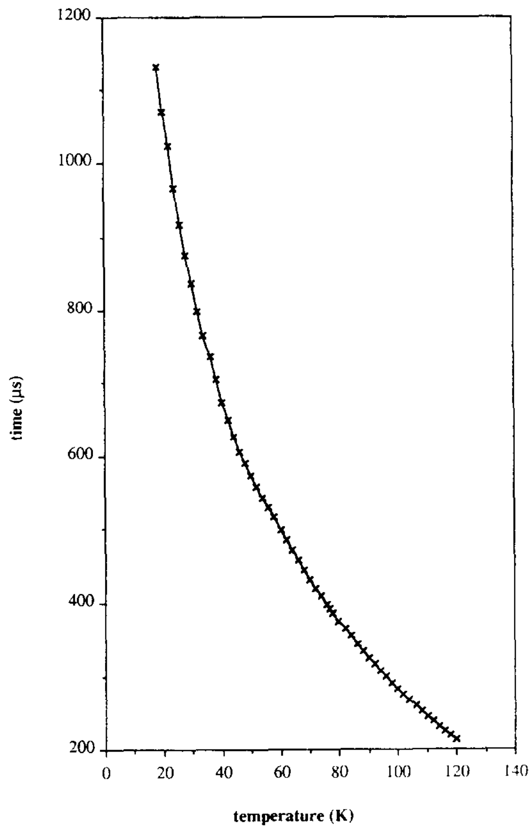

Fig. 6 Calibration curve of $CaF_2 : Yb^{2+}$

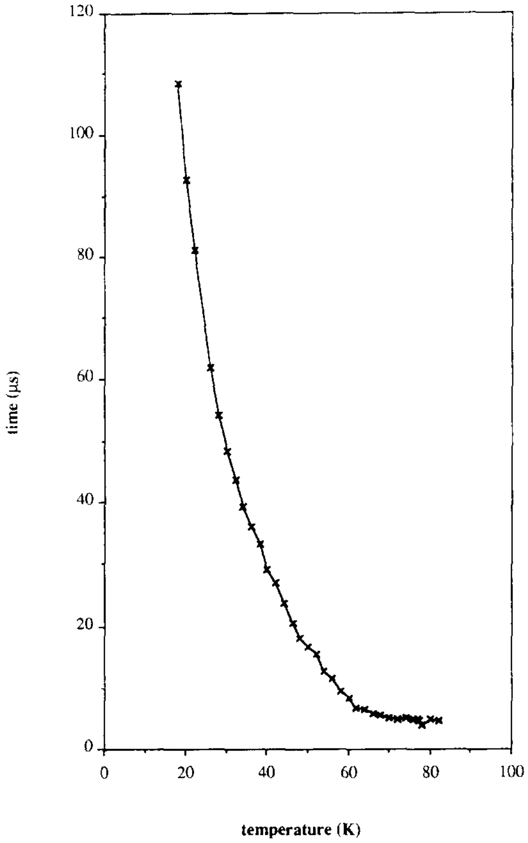

Fig. 7 Calibration curve of $SrF_2:Yb^{2+}$

($CaF_2:Yb^{2+}$ between 20 K and 60 K). These first results are very satisfying and show that our sensor is among the most effective now available in the temperature range 20 K–120 K.

To validate the optical sensor in the presence of drastic strains we implemented the two probes on a liquid hydrogen turbo-pump at 'la SEP'. This test illustrated the good behaviour of the optical probes versus thermal and mechanical strains as well as the good working of the whole sensor since temperature was measured with a precision equalling ± 0.3 K with $SrF_2:Yb^{2+}$ and ± 0.5 K with $CaF_2:Yb^{2+}$ when the turbo-pump fired.

Conclusions

We have shown that temperature measurement using the analysis of fluorescence decay-time allows the realization of optical sensors particularly resistant to harsh environments[3,8]. With a precision achieving ± 0.3 K in the presence of perturbations, this type of sensor is one of the most effective in the temperature range 20 K–120 K. The possibility of performing measurements with a high repetition rate is a further advantage of this sensor which can detect transient thermal regimes ignored by conventional electric sensors. The insensitivity of optical probes to electromagnetic and chemical oxidizing surroundings, opens up this kind of sensor to numerous applications in many scientific domains, such as microelectronics, electrical engineering, biomedicine, etc[1].

The major disadvantage of our sensor is its high cost and dimensions, but our aim was to demonstrate that the fluorescence decay-time analysis is a well-suited technique for the realization of optical temperature sensors in the cryogenic range working in very harsh environments. Nevertheless, we are working, at present, on an electronic circuit for hard calculation of the temperature, and we are studying the possibilities of developing a microchip ultraviolet laser to reduce the cost and dimensions of the sensor.

Acknowledgement

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References

1 **Grattan, K.T.V., Zhang, Z.Y.** *Fiber Optic Fluorescence Thermometry*, Chapman & Hall (1995)
2 **Noel, B.W., Borella, H.M., Francks, L.A., Marshall, B.R., Allison, S.W., Cates, M.R., Stange, W.A.** Evaluating and testing thermographic phosphors for turbine engine temperature measurements, *AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference*, San Diego (1987)
3 **Luxtron Corp.** *Model 790—a new generation of thermometry*. Santa Clara, USA (1993)
4 **Rouhet, J., Tribillon, G., Bertrand, S., Boulon, G.** Dispositif de mesure optique de température cryogénique, Patent n 9403797, France (1994)
5 **Courtois, B.** Processus de photoionisation et mécanismes de fluorescence d'ions terres rares divalents Eu^{2+} et Yb^{2+} dans des monocristaux de fluorure alcalino-terreux MF_2 (M = Ca, Sr, Ba), Thesis, Lyon France (1990)
6 **Moine, B., Courtois, B., Pedrini, C.** Luminescence and photoionisation processes of Yb^{2+} in CaF_2 and SrF_2 and BaF_2, *J Phys (France)*, **50** (1989) 2105
7 **Loh, E.** Ultraviolet absorption spectra of Europium and Ytterbium in alcaline earth fluorides, *Phys Rev*, **184** (1969) 348
8 **Noel, B.W., Turley, W.D., Lewis, W., Tobin, K.W., Beshears, D.L.** Phospor thermometry on turbine-engine blades and vanes, *Temperature: Its Measurement and Control in Science and Industry*, Vol. 6, Part 2, J.F. Schooley (Ed) (1992) 1249–1254