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Strain and temperature effects on erbium-doped fiber for decay-time based sensing

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An experimental investigation into the strain and temperature sensitivity of the fluorescence decay time in commercial erbium-doped optical fiber has been carried out. Results show that a strain effect on the performance of temperature-based sensors using such fiber is larger than that for neodymium-doped fiber, but a little smaller than is seen in similar ytterbium-doped material. For the materials studied, the relative change in lifetime ranges from about 5×10^{-7} (for Yb) to 14×10^{-7} (for Nd) $\mu\epsilon^{-1}$ and the associated error in the temperature measurement ranges from 1.8×10^{-3} (for Nd) to $6.1\times10^{-3}\,\mathrm{K}\mu\epsilon^{-1}$ for the Yb sample used. The application to simultaneous strain and temperature monitoring is discussed. © *2000 American Institute of Physics.* [S0034-6748(00)03701-1]

I. INTRODUCTION

The wider availability of a range of rare-earth-doped optical fibers, from a variety of sources and designed usually for laser or telecommunications applications, has more readily allowed their use in a number of intrinsic optical fiber sensor devices.[1] This has most usually been in optical fiber thermometry, where either an *intensity* ratio of the fluorescence arising from several (usually two) specific levels is analyzed or the fluorescence *decay time* at a particular wavelength is determined.[2,3] In the course of previous work with several types of neodymium-doped fiber, to create a fluorescence decay-time-based temperature reference for an in-fiber optically based strain sensor, a small additional strain sensitivity of that fiber was observed in research by Liu *et al.*[4] Here, an optical fiber network comprising an in-fiber Fabry–Perot étalon strain sensor was coupled with an Nd-doped fiber thermometer and some unexpected cross sensitivity of that fiber to strain effects was seen. This was investigated further for other types of Nd and Yb-doped[5] fibers and it became apparent that a study of erbium (Er)-doped fiber was essential, due to the widespread use of this material in optical fiber systems and its proven value in optical thermometry.[6]

In this work as a result, a study has been carried out of the effect of longitudinal strain (up to the level of fiber fracture) on a fluorescence decay-time-based temperature sensor scheme (in this case based on erbium-doped fiber) and the resulting potential error in uncorrected systems evaluated and quantified. Characteristics of the device over a temperature range from room temperature to $\approx 150\,^{\circ}\mathrm{C}$ are considered. Results obtained are compared with those from other similar systems and recommendations for intrinsic, optical fiber-based, simultaneous strain, and temperature sensors made.

II. THEORETICAL BACKGROUND

In sensor systems of this type, both strain *and* temperature sensitivity occur and ideally must be separable.[7] The background to simultaneous strain and temperature measurement using optical techniques has been discussed in some detail by Jones[8] and summarized previously.[1] In essence, however, two measurand-dependent observables, in this instance τ_1 and τ_2 (the fluorescence lifetimes produced by two different rare-earth-doped fibers) at a certain temperature, T, and a specific strain, ϵ, must be considered, where each shows some sensitivity to both measurands so that

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}=\begin{bmatrix}K_{1T} & K_{1\epsilon}\\ K_{2T} & K_{2\epsilon}\end{bmatrix}\begin{bmatrix}T\\ \epsilon\end{bmatrix} \tag{1}$$

such that

$$\begin{bmatrix}T\\ \epsilon\end{bmatrix}=\frac{1}{K_{1T}K_{2\epsilon}-K_{2T}K_{1\epsilon}}\begin{bmatrix}K_{2\epsilon} & -K_{1\epsilon}\\ -K_{2T} & K_{1T}\end{bmatrix}\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}, \tag{2}$$

where K_{nT} and $K_{n\epsilon}$ are coefficients of temperature and strain, respectively, for $n=1$ or 2 in this case.

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

$$|\delta T|=\frac{|K_{2\epsilon}\|\Delta\tau_1|+|K_{1\epsilon}\|\Delta\tau_2|}{|K_{1T}K_{2\epsilon}-K_{2T}K_{1\epsilon}|}, \tag{3}$$

$$|\delta\epsilon|=\frac{|K_{2T}\|\Delta\tau_1|+|K_{1T}\|\Delta\tau_2|}{|K_{1T}K_{2\epsilon}-K_{2T}K_{1\epsilon}|}, \tag{4}$$

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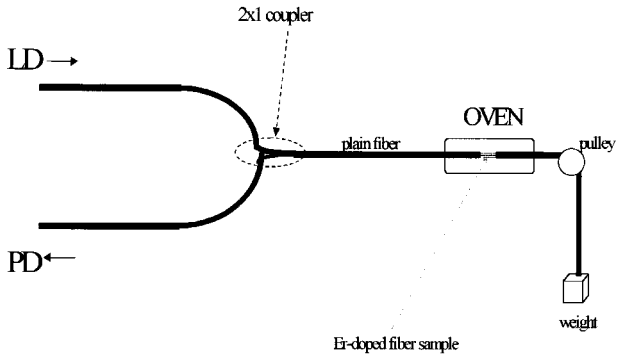

FIG. 1. Experimental arrangement used in this work.

where $\Delta\tau_n$ is the change in the lifetime, and $n=1$ or 2 in this instance.

A particular description of the simultaneous discrimination of temperature and strain based on the use of dual elements, involving for example two different doped fibers or one doped fiber combined with an alternative strain sensing element[8] is possible, in terms of the use of Eqs. (1) and (2), with the error tolerance being estimated from Eqs. (3) and (4). Fluorescence may be excited in such a doped fiber through the use of a pulse of light from an appropriate laser diode source. It is found that following the termination of the excitation light pulse, the fluorescence decay signal can be written as an exponential function of time, t, by

$$f(t)=A\exp(-t/\tau)+B,$$

where A corresponds to the initial fluorescence amplitude; τ is the corresponding fluorescence lifetime, which is temperature-dependent; and B is the signal baseline offset.

III. EXPERIMENTAL ARRANGEMENT

The experimental arrangement used was similar to that of previous work,[5,7,9] as shown in Fig. 1, and consisted of a laser diode pump (wavelength, $\lambda=813$ nm and maximum power, $P_0=40$ mW) which was modulated via an external electronic source. The 813 nm wavelength at which it operated was selected to fall within the absorption band of the Er-doped material used,[9] and the laser was coupled to one fiber input of a 2×1 coupler arrangement. The output of the coupler was connected to a length of conventional communications fiber leading to a stable tube oven (STANTON REDCROFT), into which was fusion spliced the $\sim$ 5 cm long test piece of single-mode ($\approx$3/125 μm core/cladding) Er fiber, using both high and low levels of doping, in two separate cases. This length of fiber used ensured an adequate absorption and fluorescence signal yield. The other end of the sample was fused to a similar piece of communications-type single-mode fiber. Strain was applied by using a pulley system with weights added, progressively controlling the overall strain exerted on the test fiber. Care was taken to prevent the fiber from touching the tube oven glass and to lubricate the pulley in order to minimize friction. The detector used, an InGaAs photodiode, was chosen to cover the spectral fluorescence emission range at wavelengths greater than the laser wavelength and was connected to the other input of the coupler.[9] Thus, with the system described, the temperature and strain applied to the fiber sensor could be carefully controlled and monitored.

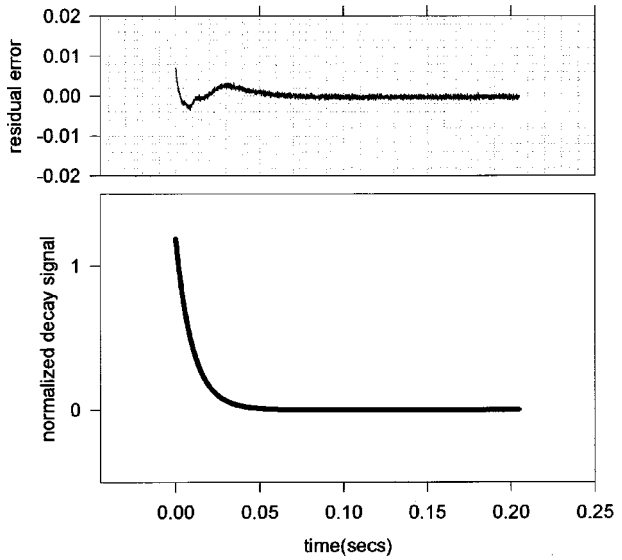

FIG. 2. Analysis of decay-time data from Er-doped fiber: upper graph—residual error vs time; lower graph—decay signal vs time.

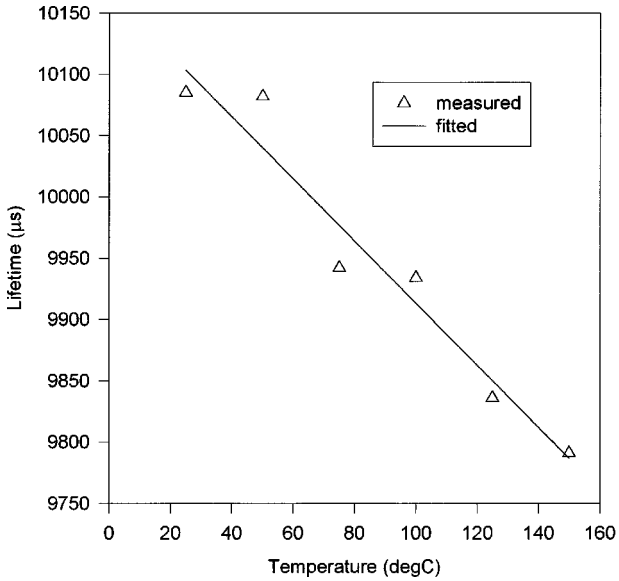

FIG. 3. Graph of fluorescence lifetime vs temperature.

It was necessary to measure the fluorescence lifetime of the doped fiber and for this task an analog-to-digital card connected to a PC was employed to process the signal electronically. The falling edge of the pulse was used to sample the output of the photodiode, obtaining the time evolution of the exponential decay in the fluorescence, with a sampling frequency of 10 kHz.

A test was first performed to estimate the range of strains which could be applied to the completed fiber system without damage. This fiber was found to break for a total load of approximately 240 g which, from a knowledge of the dimensions and mechanical properties of the fiber, corresponded to a strain, ϵ, of about $2500\mu\epsilon$ calculated from:

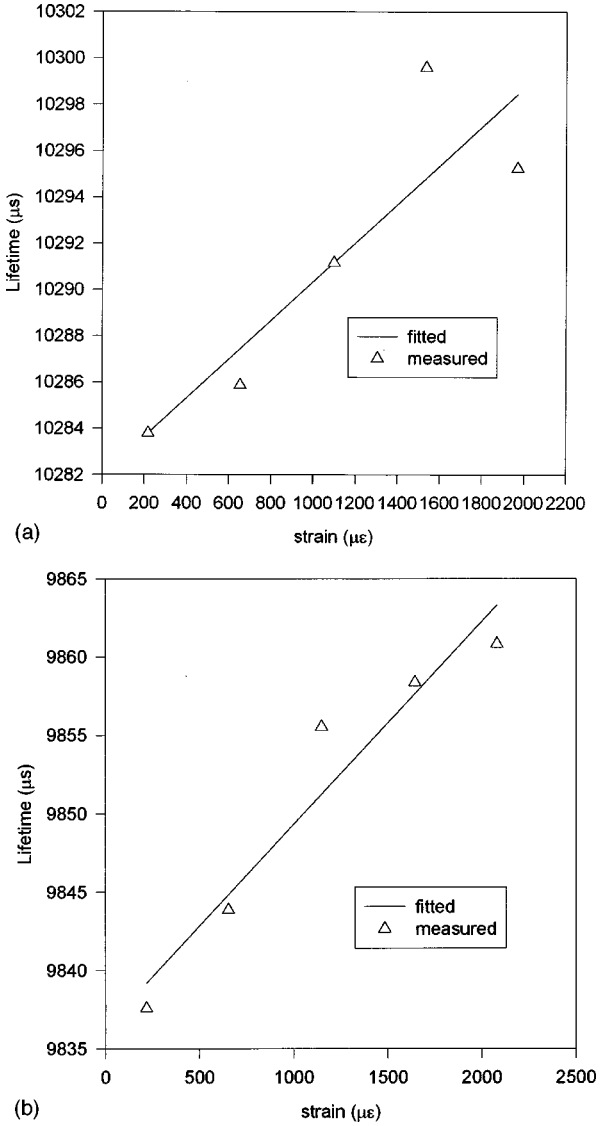

FIG. 4. (a) Plot of lifetime as a function of strain for a low doped fiber (200 ppm). (b) Plot of lifetime as a function of strain for a high doped fiber (960 ppm).

$$\epsilon = \frac{mg/A}{Y},$$

where A is the cross-sectional area of the fiber, calculated for the 125 μm diameter used, and Y is Young's modulus $(=\text{stress/strain}) = 7.31 \times 10^{10}\ \text{N/m}^{-2}$ (for fused quartz).

IV. RESULTS

A. Analysis of the decay of fluorescence

Figure 2 shows a typical data analysis result of the fluorescence signal output as a function of time. In the lower plot, the sampled data and the fitted exponential curve are shown together. All of the results of this type which were taken show similar results, with the fitted exponential being very close to the data points and without revealing a substantial mismatch. In the upper plot, it is possible to see the error, $y_{\text{sampled}}(t) - y_{\text{fitted}}(t)$, which is very small and considered not to affect the estimation of lifetime, in spite of the fact that a negligible second order effect is recognized.

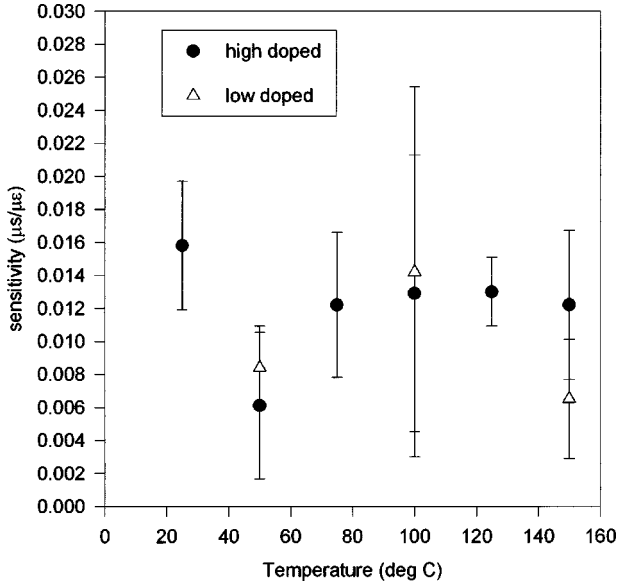

FIG. 5. Strain sensitivity of fluorescence lifetimes as a function of temperature.

The plots analyzed in this study were obtained by processing a 512 point time series with an integration run time of ≈100 min in each case. This integration time is much longer than would be useful for a sensor system, but here it was used to ensure an accurate determination of the very small strain effect present. The method of signal analysis was quite different from the previously employed phase-locked detection (PLD) method[5,7,9] or applying a non-iterative method to the results obtained;[10] but an acceptable level of error was obtained. Although the signal detected was noisy, the effects of temperature and strain on the lifetime were clearly identified and measured. The processing scheme employed a Marquardt–Levenberg algorithm for parameter estimation—an accurate tool but slow for on-line operation.

B. Temperature calibration of the system

An initial calibration of the performance of the system in terms of the decay time as a function of temperature was carried out, to check the consistency of the performance with that of previous work. This is shown in Fig. 3 for the 960 ppm dopant level in the sample over a temperature range of 20–150 °C. The figure also illustrates the dominant nature of the temperature effect upon lifetime, as will be evident from the results on strain tests at a series of fixed temperatures shown below.

C. Strain calibration of the system over the temperature range of 20–150 °C

For each of the two different Er-doped fiber types considered (200 and 960 ppm doping), a series of results was taken of the lifetime change with applied strain. Having previously determined the fiber fracture limit of $\geqslant 2500\ \mu\epsilon$, the applied strain was limited so as not to exceed this figure. Temperature increments of ≈25 °C were used for the 960 ppm fiber and ≈50 °C for the 200 ppm sample. Typical results obtained for each are shown in Fig. 4(a) for 200 ppm

TABLE I. Data on several doped fibers for sensor use.

	Er 200 ppm	Er 960 ppm	Yb 2.5%	Nd 300 ppm
Typical lifetime at 25 °C (μs)	10 350	10 100	875	365
$\frac{\partial L}{\partial \epsilon}\frac{1}{L}(1/\mu\epsilon)$	$(9.66\pm1.93)\times10^{-7}$	$(11.9\pm2.97)\times10^{-7}$	$(4.91\pm0.91)\times10^{-7}$	$(13.7\pm1.37)\times10^{-7}$
$\frac{\partial L}{\partial T}\frac{1}{L}(1/\mathrm{K})$	$-(2.41\pm0.19)\times10^{-4}$	$-(2.47\pm0.29)\times10^{-4}$	$-(0.8\pm0.1)\times10^{-4}$	$-(7.17\pm0.82)\times10^{-4}$
$\frac{\partial T}{\partial \epsilon}(\mathrm{K}/\mu\epsilon)$	4.0×10^{-3}	4.7×10^{-3}	6.1×10^{-3}	1.8×10^{-3}
$\Delta T=1000\ \mu\epsilon$ (K)	4.0	4.7	6.1	1.8

and Fig. 4(b) for 960 ppm. A least-squares regression is used to create the fitted straight lines in each case. There is some considerable degree of scatter, reflecting the signal noise and the degree of averaging undertaken, arising as it does from the small change in the decay time seen.

These results are drawn together in Fig. 5 where the slopes of the graphs, i.e., the sensitivities, are plotted for both fiber types over the full temperature range considered. The results each show quite a high degree of error, in spite of the long integration time, due to the comparatively small nature of the strain effect when compared to the temperature sensitivity. However, there appears to be no additional temperature effect in that the change in sensitivity plotted as a function of temperature shows a zero slope for both the high and low doped fibers, at an average value of $\approx 1\times10^{-2}\ \mu\mathrm{s}\,\mu\epsilon^{-1}$. This observation is consistent with results from previous work studying Yb- and Nd-doped fiber characteristics.

D. Comparison with Yb- and Nd-doped fibers

In the light of the requirement to produce a fiber optic thermometer with a minimum strain sensitivity, or a strain sensor with the maximum sensitivity and minimum temperature effect, the performance parameters of three different thermometer schemes using different doped fibers in terms of the effect of strain on temperature measurement, are compared. The other fibers considered are Nd (300 ppm) and Yb (2.5%)-doped fibers, and the results shown were obtained from previously reported work in this field.[5,7] As an index of sensitivity against strain for the temperature-based sensors, the following can be used:

$$\frac{\partial T}{\partial \epsilon}=\frac{\partial T}{\partial L}\frac{\partial L}{\partial \epsilon},$$

where T represents temperature, L lifetime, and ϵ strain showing the degree to which the apparent temperature response of the thermometer changes due to the strain applied to the fiber. The values of $\partial L/\partial T$ in units of $\mu\mathrm{s\,K}^{-1}$ are obtained using the values of $\partial L/\partial\epsilon$ in units of $\mu\mathrm{s}\ \mu\epsilon^{-1}$ (sensitivity) which are estimated from the slopes of the graphs of the type of Fig. 4. The gradients were assumed constant (this was consistent with previously reported work) for this estimation and so they are not expressed for a given temperature or strain. Table I shows the relative sensitivities of fluorescence lifetime change due to strain and temperature separately for the four fibers compared (low and high doping level of Er, and the samples of Yb and Nd) with an index of sensor performance for the equivalent variation, ΔT (in K), in the sensor output temperature for a case of 1000 $\mu\epsilon$ strain applied to the fiber.

V. DISCUSSION

An analysis of the foregoing shows it can be observed that the fluorescence lifetime of the Er-doped fiber is much longer in comparison to those of the Nd- and Yb-doped fibers at room temperature, and that the lifetime change and resulting temperature dependences are essentially similar for both the high and low-doped Er fibers and relative sensitivities of each lifetime against strain shown in Table I are very close to those reported for Nd and Yb, which indicates the possibility of discrimination between temperature and strain measurement by using several rare earth doped fibers in a single sensor arrangement. For optimization of the temperature measurement, Nd-doped appears to be still the most suitable fiber since it has the highest relative sensitivity, $(\delta L/\delta T)/L$, allowing more precise temperature measurement, as well as the lowest sensitivity to strain (for example, an error in the temperature measurement of 1.8 °C arises due to a 1000 $\mu\epsilon$ variation). This property of strain sensitivity and consequent lifetime variation could be employed for strain-temperature measurements in composite sensors.[5,7] From this point of view, Er-doped fibers seem to be in the middle range of sensitivity of the other two samples considered, with a relative sensitivity $(\delta L/\delta\epsilon)/L$ also between that of the Nd and Yb-doped fibers. The results have shown that there does not seem to be much difference in the strain dependence of the fluorescence lifetime between the use of the high and low Er-doped fibers in this work. Research is continuing to investigate a wider range of doped fiber materials to optimize sensitivity.

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