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High-Temperature fiber Bragg grating thermometer

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Abstract: The use of gratings written in tin-doped silica fibers as a thermometer for high temperature applications is described. Measurements up to ~800 °C show a significant advantage over conventional fiber gratings. A considerable blue-shift has been observed at high temperatures. If corrections for blue-shift are taken into account, the errors are smaller than ~2 ^{0}C.

Introduction: Optical fiber thermometry has recently attracted much attention because of the minimal dimension and the considerable advantages in hostile environments, such as in the presence of corrosive chemicals, high electric, magnetic or strong radio frequency (RF) fields. Two different means of sensing have been used: the fluorescence of rare earth doped or transition metal doped fibers and the fiber Bragg grating (FBG) shift ($\Delta\lambda_B$). Several materials have been used as fluorescent sources: Cr:LiSAF [1], Cr:YAG [2] and Tm [3] are just few examples. The FBG can be spliced to telecom fibers to have remote sensing and be multiplexed to detect several physical quantities simultaneously [4]. However, conventional fiber grating thermometers written in germanosilicate fibers exhibit poor stability at high T, especially if hydrogen loaded [5]. On the contrary, gratings written in Sn-doped silica (SS) fibers have been shown to be more temperature resistant than conventional materials [6]. In this paper we propose a grating temperature-sensor written in SS fiber that shows excellent reliability up to T~800 ^{0}C.

Experiment: The SS fiber preform was produced by modified chemical vapor deposition (MCVD) [7]. The fiber pulled from this preform had numerical aperture (NA)~0.1 and cut-off wavelength (λ_c)~1.3μm. Gratings were written in the SS fiber using a KrF excimer laser delivering 20 ns pulses at repetition rate (RR) ~20 Hz and pulse fluence (I_p) ~0.1 J/cm^2. Gratings with similar reflectivities were written in germanosilicate (GS), boro-germanosilicate (BGS) and hydrogen loaded telecom (HLT) fibers for comparison. A grating written in tin-germanosilicate (SGS) fiber was used as a reference. The gratings were spliced together and all of them except the one written in the SGS fiber have been placed in the furnace. The furnace temperature was raised to working temperature, stabilized for 4 hours and then decreased to room temperature. Reflection spectra were recorded before each thermal step and at intervals of 15-60 mins at working temperature. Every cycle was repeated before increasing the working temperature in steps of 100 ^{0}C. While gratings written in BGS and HLT fibers disappeared below 500 ^{0}C, gratings in the GS fiber needed 8 hours at 680 ^{0}C to be completely erased. The grating written in SS endured the treatment at 780 ^{0}C, proving the enhanced thermal stability with respect to the others. Fig. 1 illustrates the temperature dependence of the grating Bragg-shift recorded as soon as the working temperature is reached. $\Delta\lambda_B$ was assumed to be 0 at 20 ^{0}C. Corrections for the decrease in reflectivity have been applied in order to cancel the shift $\Delta\lambda_B$ given by changes in the grating strength (reduction in the average refractive index). While $\Delta\lambda_B$ can be assumed to be linear with T in short range of temperatures, at high temperatures $\delta(\Delta\lambda_B)/\delta T$ increases with T and $\Delta\lambda_B$ is better approximated by a polynomial function. This can be explained by the non-linear dependence of $\partial n/\partial T$ on T.

The time dependence of the Bragg shift has also been studied. Several measurements have been performed at the working temperature. Fig. 2 shows the time dependence of the Bragg-wavelength blue-shift observed at different temperatures. It is interesting to note that at high temperatures (T>400 ^{0}C) the dependence of the blue-shift on the temperature is very little

dependent on T. It must also be noted that $\Delta\lambda_B$ is a reversible shift and it disappears when the fiber is cooled down to the room temperature. This behavior can be explained by the co-existence, at high temperature, of two different defect configurations separated by a potential barrier. The states have different polarizability and the decrease in the refractive index is explained with the change of the number of defects in each configuration. When the temperature is then decreased, all the defects return to one single configuration and the refractive index increases to the original value.
The data of fig. 2 can be fitted with a two-parameters exponential-decay function:

$$\Delta\lambda_B = \Delta\lambda_{B0} - \Delta\lambda_{BT}\left(1 - e^{-\frac{t}{\tau}}\right) \qquad (1)$$

where $\Delta\lambda_{B0}$ represents the instantaneous shift observed in the Bragg grating when heated up, $\Delta\lambda_{BT}$ the time-dependent blue-shift component of $\Delta\lambda_B$ and τ the time constant of the shift. While τ was approximately constant (~1.83) all over the range of investigated temperatures, $\Delta\lambda_{B0}$ resulted to be temperature dependent.
Tab. 1 shows the values of $\Delta\lambda_{BT}$ used to fit the data of fig. 2 with eq. 1. While $\Delta\lambda_{BT}$ changes abruptly with the temperature below 300 ^{0}C, at higher temperatures the increase is small and $\Delta\lambda_{BT}$ can be approximated by the function:

$$\Delta\lambda_{BT} = \Delta\lambda_\infty - \frac{\Delta\lambda_T}{(T - T_0)^\theta} \qquad (2)$$

where $\Delta\lambda_\infty$=1.68, $\Delta\lambda_T$=1.59, T_0=167 and θ=0.0383.

The repetition of thermal cycle for each temperature shows that the Bragg shifts exhibit an excellent repeatability. In particular, the use of equations 1 and 2 allows an excellent reproducibility at high temperatures. When the mathematical corrections 1 and 2 have been adopted, the error in $\Delta\lambda_B$ (thus in T) has always been smaller than 2 degrees. It is possible define an error as ε:

$$\varepsilon = T_{corr} - T_{furn} \qquad (3)$$

where T_{furn} and T_{corr} represent the temperature of the furnace and the measured T corrected with (1) and (2). The furnace temperature was calibrated using a Pt/Pt:Rh thermocouple.
Fig. 3 shows the time dependence of ε at working temperature for several temperatures. ε is temperature independent and is $\varepsilon \leq 2$ at any temperature.
The error is given mainly by two contributions: the stability of the furnace temperature measurement and the accuracy in the Bragg shift measurement. ε is comparable with the overall experimental error. In fact the accuracy in the temperature measurements was estimated to be ~2 ^{0}C.

Conclusions: The enhanced thermal stability of gratings written in the tin doped fibers has been used to develop a minimal-intrusion fiber-thermometer that can be used up to ~800 ^{0}C. The mean of sensing is the Bragg wavelength shift. The characteristic curve has been produced and proposed in fig. 1. A reversible blue-shift has been observed after few minutes spent at the working temperature. This shift can be approximated with a decreasing exponential function. The maximum amplitude of the shift is temperature dependent below 400 ^{0}C and relatively temperature insensitive above 400 ^{0}C. If the corrections for the blue shift are taken into account, errors smaller than ~2 ^{0}C are observed in the whole range of temperatures.

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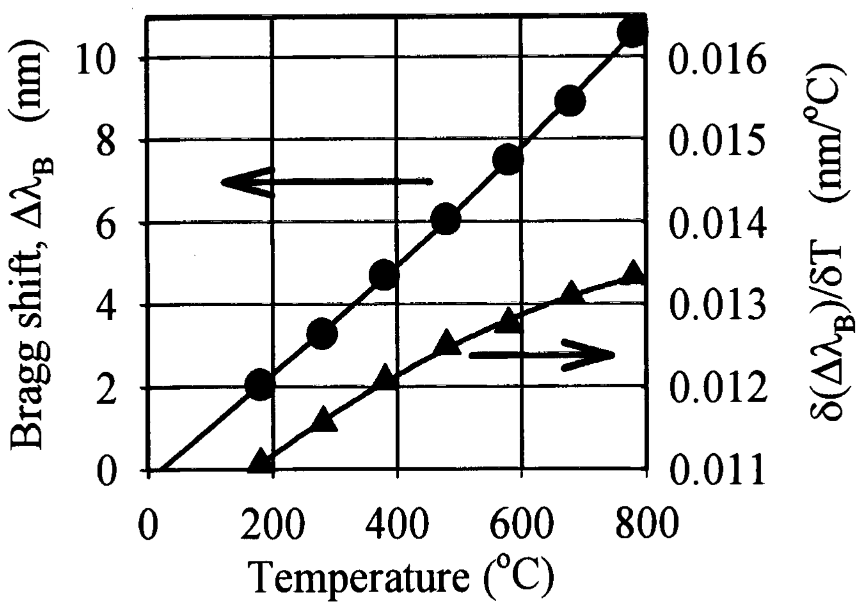
Figure captions:

Fig. 1. Dependence of Bragg shift $\Delta\lambda_B$ and its derivative $\delta(\Delta\lambda_B)/\delta T$ (nm/°C) on temperature T in the SS fiber. $\Delta\lambda_B$ was assumed to be 0 at 20 ^{0}C.

Fig. 2. Time dependence of Bragg shift $\Delta\lambda_{BT}$ for several temperatures T in the SS fiber. $\Delta\lambda_{BT}$ was assumed to be 0 when the working temperature is reached.

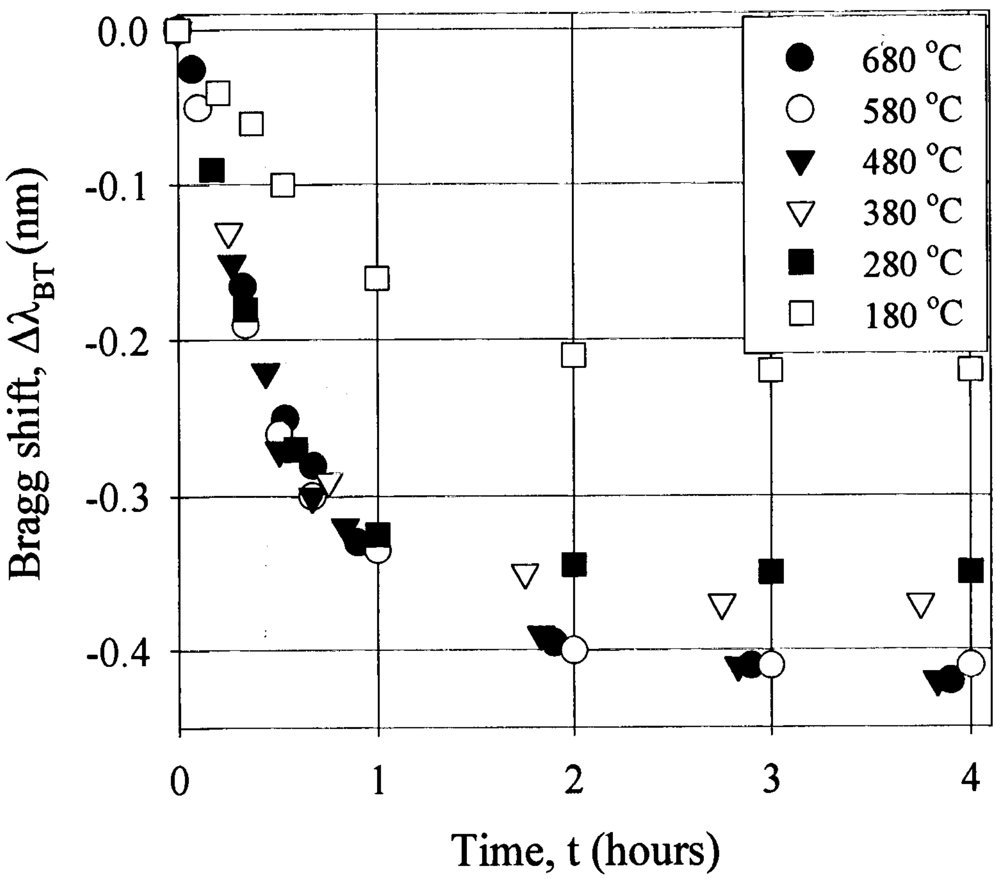
Fig. 3. Error ε of the measures taken over a period of 4 hours for several temperatures T.

Fig. 1



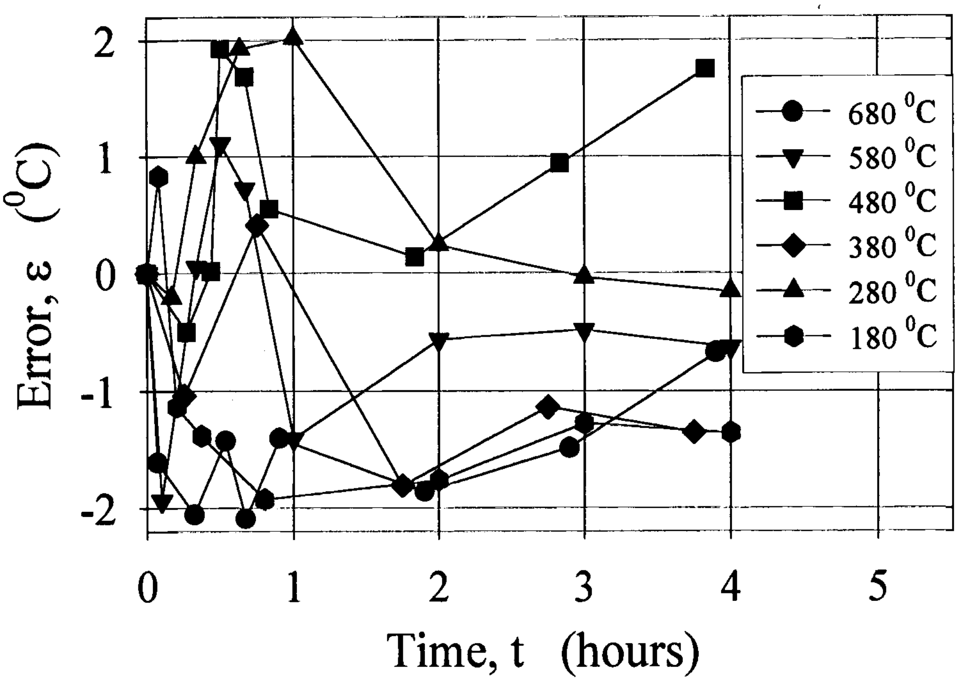
Bragg shift, Δλ_B (nm)
0
2
4
6
8
10
0.011
0.012
0.013
0.014
0.015
0.016
δ(Δλ_B)/δT (nm/°C)
0
200
400
600
800
Temperature (°C)

Fig. 2



0.0
-0.1
-0.2
-0.3
-0.4
Bragg shift, $\Delta\lambda_{BT}$ (nm)
0
1
2
3
4
Time, t (hours)
680 °C
580 °C
480 °C
380 °C
280 °C
180 °C

Fig. 3



2
1
0
-1
-2
Error, ε (^{0}C)
0
1
2
3
4
5
Time, t (hours)
680 ^{0}C
580 ^{0}C
480 ^{0}C
380 ^{0}C
280 ^{0}C
180 ^{0}C

TABLES

T (^{0}C)	$\Delta\lambda_{BT}$
180	0.234
280	0.352
380	0.384
480	0.406
580	0.414
680	0.428

Tab. 1 Temperature dependence of the blue shift in the SS fiber. T represents the working temperature, $\Delta\lambda_{BT}$ the asymptotic value of the Bragg-wavelength blue-shift at the temperature T.