TEMPERATURE AND STRAIN EFFECTS DISCRIMINATION INTO COMPOSITE MATERIALS WITH EMBEDDED DUAL TYPE I-IA FIBRE BRAGG GRATINGS

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Abstract

Fibre Bragg gratings (FBGs) are strain sensors that can be embedded into composite materials, without affecting their mechanical performances. In this study, we report the use of a dual FBGs configuration cascaded in a single co-doped boron/germanium photosensitive optical fibre. The first FBG is a standard type I grating while the second one is a regenerated type IA grating, both inscribed using a 1060 nm period phase mask. The manufacturing of the type IA grating is obtained in two steps: the optical fibre is first exposed during a few minutes to a blank UV beam in order to slightly increase the core refractive index and then it is submitted in the fabrication process of the FBGs. The two types of embedded gratings exhibit a 3 pm/°C differential temperature sensitivity while they respond equally to strain providing an intrinsic discrimination between temperature and strain effects.

1 Introduction

Due to their high mechanical resistance and their lightweight in regards to metallic materials, composite materials are more and more encountered in various fields such as aeronautic, railway or wind energy production. Structural health monitoring (SHM) of composite structures is an essential add-on to determine correct maintenance or repair services during the 'life time' of the materials. It can also be applied during the fabrication process itself in order to assess the final product quality. Indeed, composite materials present residual strains resulting from the manufacturing process, which depend on the type of composite constituents and the lay-up process. These strains mainly arise from the difference in thermal expansion between the two constituents of composite materials, i.e. the reinforcement fibres and the resin (or matrix). Their measurement yields pertinent information about the integrity of the molded composite materials. Among the techniques used for strain measurements, the major field of research concerns the application of optical fibre sensors [1-4], which have a number of well-known advantages including insensitivity to electromagnetic interferences, small dimensions, light weight, multiplexing capabilities and resistance to corrosion.

Fibre Bragg gratings (FBGs) are very well suited fibre optic strain sensors that can be embedded into composite materials, without affecting their mechanical performances. The monitoring of their spectral response (more particularly the shift of their Bragg wavelength) yields quantitative information about the external perturbation. However, as strain and temperature result both in a Bragg wavelength shift, a unique uniform FBG cannot resolve these two perturbations simultaneously. Different solutions have been proposed to alleviate this limitation, such as the use of FBGs in two different optical fibres [5], FBGs written into polarization maintaining fibres [6] or hybrid FBG and long period fibre gratings [7]. For different reasons, these schemes fail to work in the particular case of composite materials, where the optical fibre gets stuck within the resin matrix.

In this study, we report the use of a dual FBGs configuration cascaded in a single co-doped boron/germanium photosensitive optical fibre. Before the inscription of the gratings the co-doped fibre is treated, to increase its photosensitivity, with a process of infusion of hydrogen during 24 h (in an autoclave at 70 °C and ~200 atm). The first FBG is a standard type I grating while the second one is a regenerated type IA grating. They are both inscribed using a 1060 nm period uniform phase mask (Λ_B=530 nm) and a 488 nm frequency doubled Ar^+ laser. The manufacturing of the type IA grating is obtained in two steps. First the optical fibre is exposed during a few minutes to a blank UV beam in order to slightly increase the core refractive index. And after the subsequent writing of a type IA FBG is made with standard writing parameters (i.e. similar mean optical power and writing time as for a type I grating). All the steps for the FBG inscription including the photo-bleaching are performed with the same UV laser at 244 nm.

The two types of gratings exhibit differential temperature sensitivity while they respond equally to strain. Hence, with a straightforward spectral de-convolution, they naturally provide a well-conditioned system that allows an intrinsic discrimination between temperature and strain effects. Such dual FBGs are embedded between two layers of the composite material sample (woven fabric glass fibre) realized by the hand lay-up technique. They are used for residual strain monitoring during the composite material molding as well as for traction and flexural strain monitoring in 4-points bending system. In all the cases, discrimination between temperature and strain effects is achieved.

2 The dual type I-IA FBGs pair

The proposed configuration consists of two FBGs separated approximately by 2 cm, according to the scheme of figure 1. The fabrication process is optimized to reduce the fibre handling. The phase mask is aligned in such a way that it is possible to proceed to the writing of the type I FBG and to the photo-bleaching preparatory for the type IA FBG in a single operation by moving the laser beam along the phase mask.

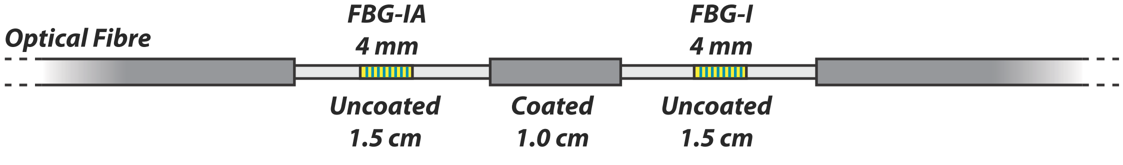

Figure 1. Disposition of the two FBGs. The striping task is carried mechanically with a previous chemical attack.

The photo-bleaching process increases the effective refractive index of the fibre core, which is monitored by observing the attenuation peak in the band 1350-1500 nm (peak is positioned near 1400 nm while the reference is at 1350 nm, as shown in figure 2).

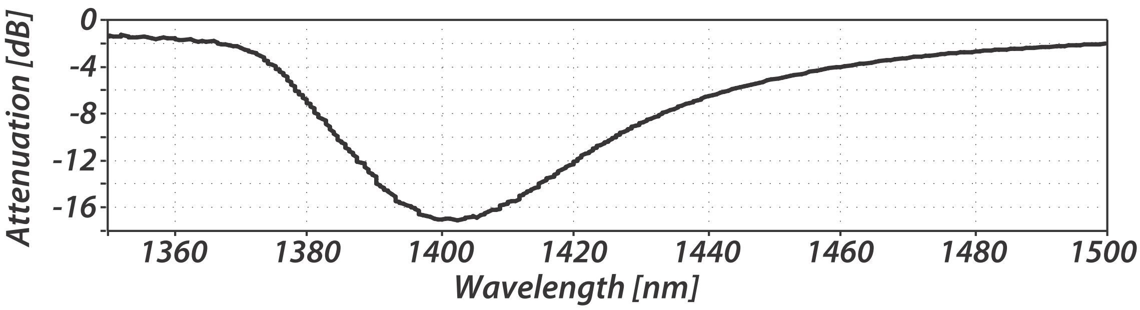

Figure 2. Attenuation as a function of the wavelength at the end of the photo-bleaching.

A change in the effective refractive index generates different temperature sensitivity while the strain sensitivity remains unchanged [8-9]. Attenuation of the order of 16 dB corresponds to an effective index variation of about 0.0107 (through $\Delta n_{eff} \approx (\lambda_{BIA} - \lambda_{BI})/2\Lambda$), resulting in a change from 1.4486 to 1.4594 according to what is presented in table 1 while the Bragg wavelength passes from about 1536.61 nm to 1548 nm. The values in the Bragg wavelength are subject to small variation due to the stress introduced to the fibre (to ensure its alignment in the clamps), to the distance between the mask and the fibre and, finally, to the temperature of the clean room.

FBG type	**Photo-Bleaching Attenuation [dB]**	$\mathbf{n_{eff}}$	$\boldsymbol{\lambda_B}$ **[nm]**	**Bare FBG's** $\mathbf{k_T}$ **[pm/°C]**
I	0	1.4486	1536.61	9.56
IA	16	1.4594	1547.995	8.84

Table 1. Attenuation peak in the 1350-1500 nm band, effective index, Bragg wavelength and temperature sensitivity variation after the photo-bleaching.

In our experiment, in order to have the proper intensity in the photo-bleaching process we used a UV power of 94 mW overall the uncoated length (L=1.5 cm) with a sweep velocity v of 1 mm/s in 30 passes (N). The resulting exposition time (t_e) is about 450 s according to:

$$t_e = \frac{NL}{v} \tag{1}$$

The velocity, the UV laser power, the exposition time and the length of the photo-bleached zone are physical parameters that change the value of the attenuation peak. The growth of the attenuation peak, generally, is bigger in the first sweep passes and rapidly saturates after a few tens of sweeps.

The differential sensitivity obtained in a bare FBG for a 16 dB attenuation peak is about 0.72 pm/ºC according to the results in figure 3. Depending on the purpose, it is possible to have greater attenuation peak and, consequently, a bigger differential sensitivity to temperature simply by tuning v, N, L and the UV power.

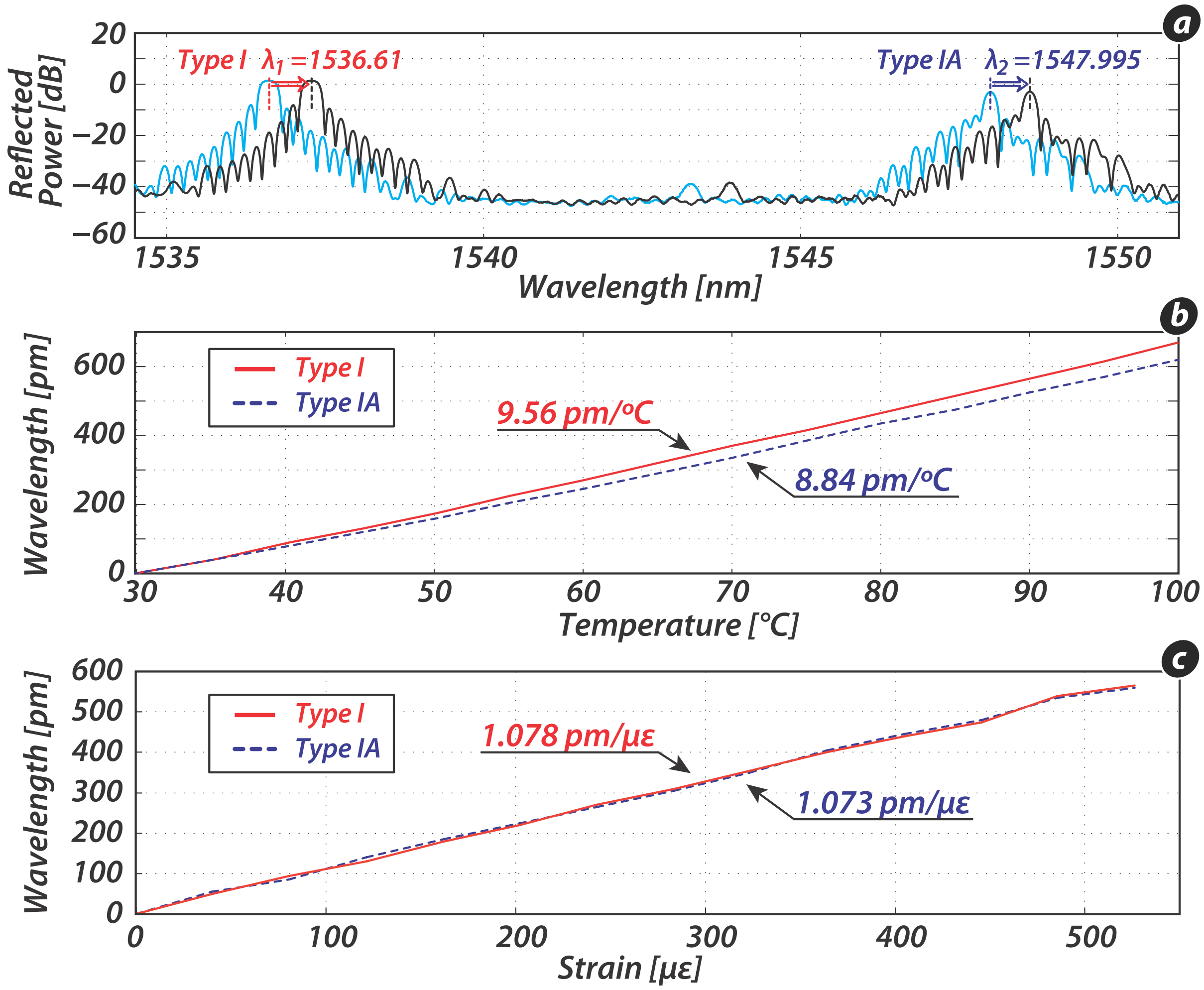

Figure 3. Spectrum change (a) and Bragg wavelength variation (b) during a temperature test in the range [30:100] ºC; Bragg wavelength variation during a traction test (c) in the range [0:525] με for a bare dual type I-IA FBG pair.

The type I FBG is inscribed with a 24 mW UV power and a beam sweep velocity of 300 µm/s over a 4 mm length, centered in the dedicated FBG-I area. Before proceeding to the inscription of the type IA FBG, it is important to wait a 2 hours settling time so that hydrogen can diffuse again in the photo-bleached zone. The type IA FBG is photo-written in the photo-bleached uncoated fibre with 39 mW UV power and a beam sweep velocity of 20 µm/s, over a 4 mm length. The bare dual I-IA FBG pair production process terminates with the annealing at 90 ºC during about 24 h to stabilize the hydrogenated FBGs with respect to temperature. In the hypothesis of homogenous distribution of temperature and strain for the two FBGs we have [8]:

$$\begin{bmatrix} \Delta\lambda_I \\ \Delta\lambda_{IA} \end{bmatrix} = \begin{bmatrix} k_{\varepsilon I} & k_{TI} \\ k_{\varepsilon IA} & k_{TIA} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} \tag{2}$$

Where $k_{\varepsilon I}$, $k_{\varepsilon IA}$, k_{TI}, k_{TIA} are the strain and temperature constants for the type I and IA FBGs respectively. $\Delta\lambda_I$ and $\Delta\lambda_{IA}$ are the Bragg wavelength variations of the type I and IA FBGs, $\Delta\varepsilon$ the strain variation and ΔT the temperature variation. In our case we have $k_{\varepsilon I} = k_{\varepsilon IA}$, giving a differential sensitivity only between k_{TI} and k_{TIA}, as shown in figure 3c. Thus, inverting the system, we have:

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} \frac{-k_{TIA}}{\Delta k_T} & \frac{k_{TI}}{\Delta k_T} \\ \frac{1}{\Delta k_T} & \frac{-1}{\Delta k_T} \end{bmatrix} \begin{bmatrix} \Delta\lambda_I \\ \Delta\lambda_{IA} \end{bmatrix} \tag{3}$$

Where $\Delta k_T = k_{TI} - k_{TIA}$. The relation 3 can be simply used to separate strain and temperature knowing the two Bragg wavelength shifts.

3 Embedding and characterization of the dual I-IA FBGs pair

The embedding process [10] was carried in woven fabric glass fibre (figure 4a). During the process, two samples — with two dual I-IA FBGs pairs for each one — were made at the same time with the hand lay-up technique. All the layers, pre-moistened in epoxy resin (Araldite LY 3505), are positioned parallel to the fibres as shown in figure 4b. The total number of layers is 24 and the two FBGs pairs are positioned between the layers 5 and 6 and between the 19 and 20. To avoid ruptures during the handling, the optical fibres are protected with a 900 µm jacket at sample interfaces. The samples are cured in an oven during a day at 80 ºC. During this curing process, FBGs spectrum shapes have been monitored in order to check if they undergo the same internal stresses. We note a slight shape distortion during the cooling phase to ambient temperature. In figure 4c we present one of the resulting samples after the cutting task.

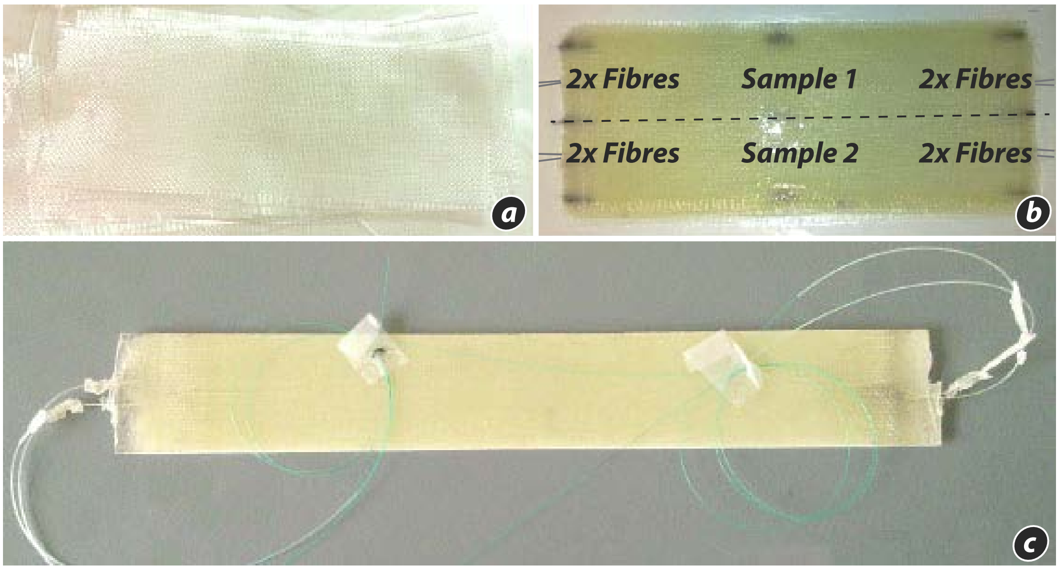

Figure 4. The woven glass fibre (*a*) layers are positioned parallel to make two samples with two FBGs pairs for each one (*b*). In (*c)* we have the resulting sample after the cutting.

The characterization process is composed by three separated tests: traction test, 4-points flexural test and temperature test. The two stress tests are performed according to the illustration in figure 5.

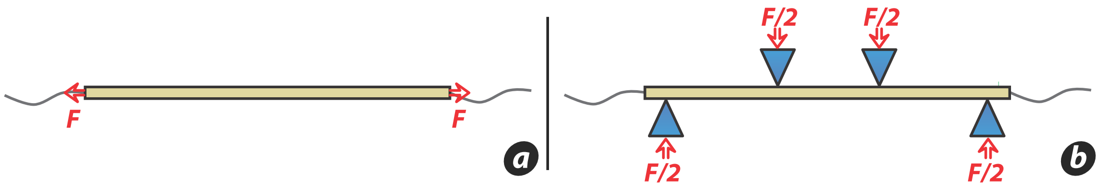

Figure 5. Traction (*a*) and 4-points flexural stress (*b*) test schemes.

The traction test was performed with a force ranging from 0 to 1000 daN with steps of 100 daN, while for the 4-points flexural test, a 0 to 30 daN range with steps of 5 daN is used. The type I FBG exhibits a traction sensitivity of 3.24 pm/daN and a 4-points flexural stress sensitivity of 83.17 pm/daN. For the type IA FBG, the sensitivities are about 3.26 pm/daN for traction and 79.67 pm/daN for bending respectively. The 4-points bending test presents different sensitivities probably due to the fact that the FBGs are not perfectly placed with respect to the center of the bending set-up, thus generating a different flexural effect. The traction test (figure 6) demonstrates that we have the same strain sensitivity in the two FBGs ($k_{\varepsilon I} = k_{\varepsilon IA}$) for a Bragg wavelength variation over 3 nm.

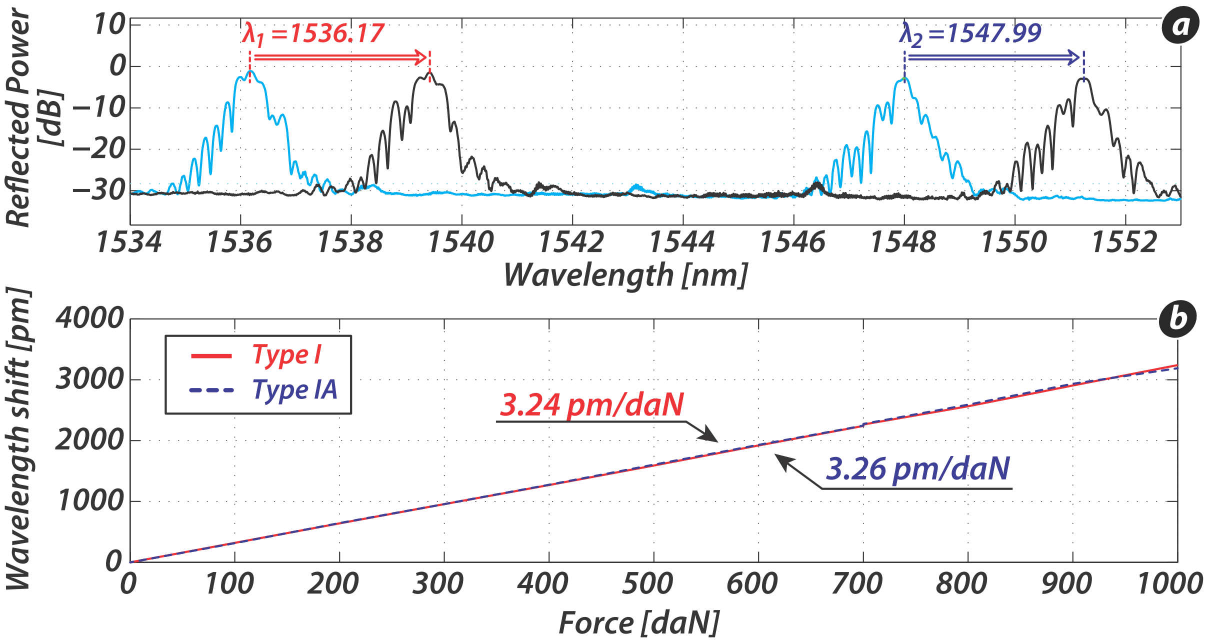

Figure 6. Spectrum change (a) and Bragg wavelength variation (b) during a traction test in a force range of [0:1000] daN for the glass fibre woven fabric composite.

During the temperature test (figure 7), we obtained a temperature sensitivity of 24.75 pm/ºC for the type I FBG and of 21.63 pm/ºC for the type IA FBG. The differential temperature sensitivity is 3.12 pm/ºC, allowing a good discrimination between temperature and strain using formula 3.

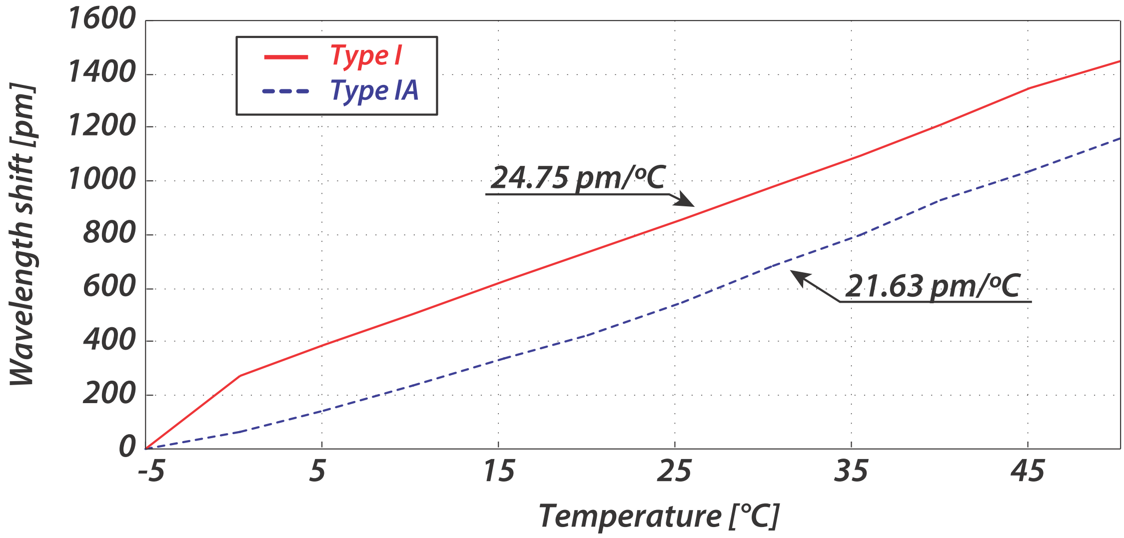

Figure 7. Bragg wavelength variation during a temperature test in the range [-5:50] ºC.

4 Conclusion

In this paper we presented results of dual type I-IA fibre Bragg gratings embedded in a glass composite material. We resume the different sensitivities obtained in the table 2.

FBG type	4-points bending sensitivity [pm/daN]	Traction sensitivity [pm/daN]	Temperature sensitivity [pm/°C]
I	83.17	3.24	24.75
IA	79.67	3.26	21.63

Table 2. Sensitivities for the 4-points bending, traction and temperature tests.

Thanks to the type IA grating, we obtained a perfect match for the traction sensitivity whereas the differential temperature sensitivity is over 3 pm/°C. It will thus provide an intrinsic discrimination between temperature and strain effects.

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