Annealing-induced stress changes in UV-irradiated germanium-doped fibers

F. Dürr, H. G. Limberger, and R. P. Salathé
Ecole Polytechnique Fédérale de Lausanne (EPFL), Advanced Photonics Laboratory, CH-1015 Lausanne, Switzerland
Tel.: +41 (21) 693 51 83, Fax: +41 (21) 693 37 01,, hans.limberger@epfl.ch

S. A. Vasiliev, O. I. Medvedkov, A. S. Bozhkov, and E. M. Dianov
Fiber Optics Research Center at the General Physics Institute of the Russian Academy of Sciences, 119991 Moscow, Russia
Tel.: +7 (095) 132 83 06, Fax: +7 (095) 135 81 39, sav@fo.gpi.ru

Abstract
Stress changes due to annealing have been measured tomographically in UV-irradiated germanium-doped fibers and correlated with the aging curves of the UV-induced refractive index change. For demarcation energies < 3 eV, a linear correlation between index and stress is found.

Introduction. Thermal annealing experiments of UV-written Bragg gratings serve as a means to gather information about the composition of the index change from distributions with different thermal stability and thus allow predictions about the long-time stability of refractive index changes [1, 2]. Stress measurements can be used to identify the compaction-induced index change triggered by UV-irradiation [3]. Here, we combine the two techniques to evaluate the thermal stability of the UV-induced compaction and its contribution to the overall refractive index change in fiber gratings.

Experiment. The fiber under investigation has been fabricated by MCVD technique at FORC and is doped with 14 mol% germanium in the core. A Lloyd interferometer was used to write Bragg gratings at five different total doses with 244 nm cw-irradiation and a writing intensity of 50 W/cm^2. The gratings were annealed using the technique described in [2, 4]. The attempt frequency was determined to be $\nu_0=10^{13}$ Hz by comparison of annealing curves measured for three different temperature sweeps, and thus, the refractive index change could be presented as a function of demarcation energy for each total dose [4].

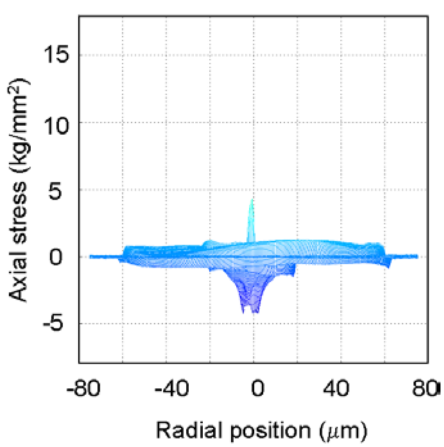

Fig. 1: Axial two-dimensional stress profile of the pristine fiber.

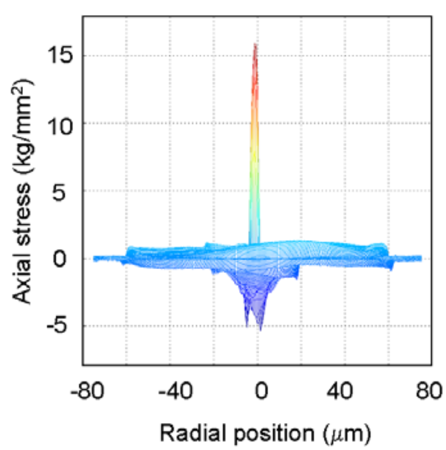

Fig. 2: Axial core stress increase after irradiation with a total dose of 150 kJ/cm^2.

Six fiber samples have been prepared for stress measurements. In each sample, six regions of 0.4 mm in length, separated by five regions of equal length, have been irradiated homogeneously with total doses of 1, 3, 10, 30, 100, and 150 kJ/cm^2, respectively. Five of the six fiber samples have subsequently been annealed in a computer-controlled furnace, using a linear temperature sweep of 0.25 K/s. The annealing was stopped when the samples had reached temperatures of 496, 827, 992.5, 1158, and 1323 K, corresponding to demarcation energies of 1.5, 2.5, 3, 3.5, and 4 eV, respectively.
The two-dimensional stress profiles were measured using a setup similar to the one presented in [5]. The axial stress induced phase retardation profile of the fiber is determined polarimetrically for seven different projection angles, equally spaced by 30° and covering a total range of 0 - 180°. To improve the quality of the reconstructed images, projection data between the measured data were interpolated. The axial stress profile was then calculated by inverse Radon transformation of the projection data [5].

Results and discussion. In Fig. 1, the tomographic axial stress profile of the pristine fiber is presented, and can be compared to the stress profile after irradiation with 150 kJ/cm^2 (Fig. 2). The axial core stress is found to increase considerably from 4.4 kg/mm^2 up to 16 kg/mm^2 after UV-irradiation. For all samples under investigation, tomographic stress profiles as shown in Figs. 1 and 2 were captured along the fiber with an axial resolution of 56 µm. The resulting axial core stress distribution is shown in Fig. 3 for the non-annealed sample. The higher the total dose, the higher is the increase in axial core stress in the respective region. For the region irradiated with the highest total dose (z=0 in Fig. 3), a saturation of core stress increase can be found. In Fig. 4, the increase in axial core stress is correlated with the change in refractive index. As reported in [6] for pulsed irradiation, a linear relation between stress and index change is found, expect for the highest irradiation dose. The slope of the linear fit to the data (except the highest irradiation dose) is ~1 kg/mm^2, which is within the range of 1/(0.8+/-0.2) kg/mm^2 found in [6].

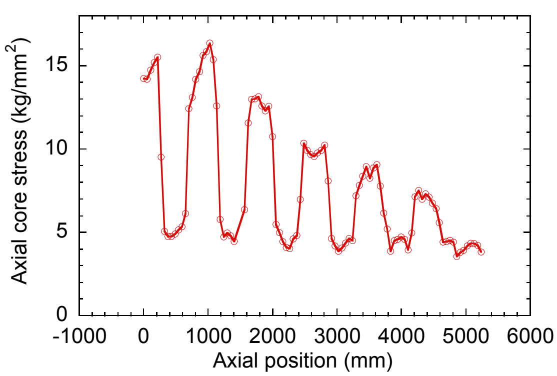

Fig. 3: Evolution of core stress as a function of total dose measured for the non-annealed sample.

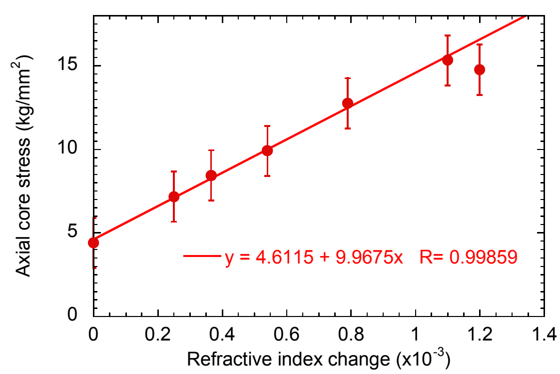

Fig. 4: A linear correlation of stress with index change is found.

The changes in axial core stress have been observed as a function of temperature or demarcation energy. Therefore, we distinguish between UV-induced core stresses σ_{Co}^{UV} and residual core stress σ_{Co}^{res} introduced into the fiber during fabrication [7]:

$$\sigma_{Co}^{tot}(E_d) = \sigma_{Co}^{res}(E_d) + \sigma_{Co}^{UV}(E_d), \tag{1}$$

where E_d is the demarcation energy of the respective sample. The evolution of residual core stress with demarcation energy was obtained by observing the non-irradiated parts of the fiber and is shown in Fig. 5. The increasing stress for demarcation energies $E_d > 1.5$ eV is explained by the annealing of drawing induced compressive core stresses [7]. We adopted the results of Mohanna *et al*. [8] for internal stress relaxation in optical fibers for comparison with our data and found a reasonable agreement (Fig. 5).

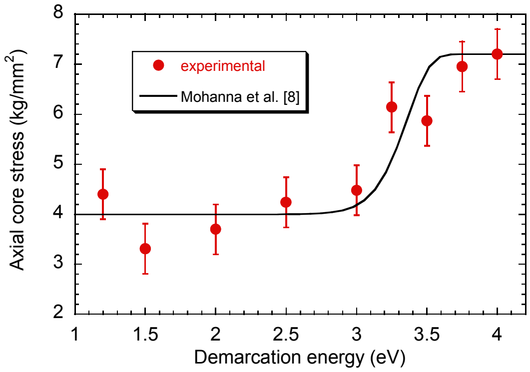

Fig. 5: Residual axial core stress as a function of demarcation energy for the pristine fiber.

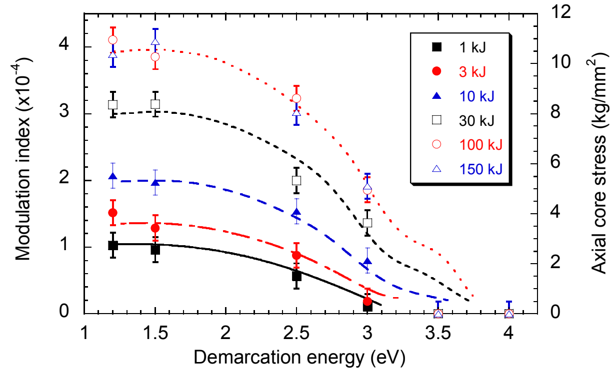

Fig. 6: Correlation of index modulation and UV-induced axial core stress changes for six different total doses.

In Figure 6, the changes in UV-induced axial core stress calculated according to equation 1 are illustrated as a function of demarcation energy. For $E_d < 3$ eV, a linear correlation between refractive index and stress is found. However, the UV-induced axial core stress disappears for $E_d \geq 3.5$ eV, although there remains still a significant amount of UV-induced refractive index. The refractive index change thus consists of at least two different contributions. The first contribution vanishes for $E_d < 3.5$ eV and is accompanied by a compaction of the core glass and a corresponding stress increase [3, 6]. For this contribution, two Gaussian energy distributions of defects have been identified in [4]. The other contribution withstands demarcation energies in excess of 3.5 eV. It might be originated from dopant diffusion at high temperature, resulting in so-called chemical composition gratings [9]. No difference in annealing behavior can be observed for the two highest doses of 100 kJ/cm^2 and 150 kJ/cm^2, respectively. By comparison of Fig. 5 and 6, it can be found that the UV-induced stresses anneal at considerably lower demarcation energies/temperatures than the drawing-induced stresses.

Conclusion Stress changes due to annealing have been observed for pristine as well as UV-irradiated germanium-doped fiber samples and correlated with refractive index annealing data. For demarcation energies below 3.5 eV, a linear correlation between stress and index is found. For higher demarcation energies, the stress is found to vanish, whereas remains of refractive index can still be observed. The UV-induced stresses anneal at lower demarcation energies in comparison to the drawing-induced stresses.

References

[1] T. Erdogan *et al.*, *Journal of Applied Physics* **76**, pp. 73-80, (1994).

[2] J. Rathje *et al.*, *Journal of Applied Physics* **88**, pp. 1050-1055, (2000).

[3] H. G. Limberger *et al.*, *Applied Physics Letters* **68**, pp. 3069-3071, (1996).

[4] S.A. Vasiliev *et al.*, *BGPP 2003, paper MD 31*, pp. 145-147, (2003).

[5] Y. Park *et al.*, *Optics Letters* **27**, pp. 1217-1219, (2002).

[6] P.-Y. Fonjallaz *et al., Optics Letters* **20**, pp. 1346-1348, (1995).

[7] W. Hermann *et al.*, *Applied Optics* **28**, pp. 1980-1983, (1989).

[8] Y. Mohanna et al., *Journal of Lightwave Technology* **8,** pp. 1799-1801, (1990).

[9] M. Fokine, *Optics Letters* **27,** pp. 1016-1018, (2002).