Fabrication of fiber Bragg gratings in 40 μm diameter low GeO_2 silica fiber using cw-Ar^+-laser

Hans G. Limberger, Georgios Violakis
Ecole Polytechnique Fédérale de Lausanne (EPFL), IMT
CH-1015 Lausanne, Switzerland
hans.limberger@epfl.ch

Frédéric Sandoz, Carlos Pedrido
Silitec SA
Route de la Gare 70, CH-2017 Boudry, Switzerland

Abstract: Mean index changes $>10^{-3}$ were obtained in non-hydrogen-loaded ~3% GeO_2-doped silica fibers with a 9/40 μm core/cladding diameter using a cw 244-nm-Ar^+-laser. Core stress changes are positive indicating a compaction contribution to the index change.

OCIS codes: (060.3738) Fiber Bragg gratings, photosensitivity; (060.2340) Fiber optics components

1. Introduction

Fibers with external diameter considerably smaller than standard size 125 μm fibers have certain advantages. They can be smaller packaged as they have an enhanced resistance to mechanical failure through static bending fatigue: The stress at the fiber surface induces intrinsic and microscopic surface flaws to grow and increases with fiber radius. On the other hand the breaking stress is characteristic for the material and the fiber fabrication. As the surface stress reduces with external diameter for the same bending radius the fibers are more resistant to static fatigue if they have they have the same proof test level. In addition, small diameter fibers have a smaller stiffness and are thus easier to stretch, which may enhance their sensitivity in sensor applications.

First fiber Bragg gratings have been fabricated in fibers with diameters as small as 40 μm, a core size of 8.5 μm, and core-cladding relative index difference of 0.35% by Takeda et al. [1] using fibers from Hitachi Cable Ltd. [2]. As the fibers contain only a small amount of germanium the fibers were hydrogen loaded for grating fabrication using a KrF laser and phase mask technique.

In fact low germanium doped fibers are considered to be of low photosensitivity under irradiation into the 240-nm band. Index changes have been reported to be below 6×10^{-5} [3] [4] [5] using KrF (248 nm) or cw Ar^+ (244 nm) irradiation [6]. To increase strongly the photosensitivity boron co-doping [6] and H_2 loading [3] [4] have been invented. However, using a pulsed XeCl-pumped dye laser operating at 240 nm we recorded fiber Bragg gratings with index changes as high as 1.2×10^{-3} in standard telecommunication fiber [7]. Our results were explained by the ultra-high stability of the Lloyd interferometer and the long irradiation times used.

In this work we report about the fabrication of short fiber Bragg gratings in a low germanium doped fiber (3.3 mol%) using a cw-Ar^+ laser operating at 244 nm. The index changes that are 20 times higher than reported so far are attributed to 1) a high stability of the phase mask set-up; and 2) to a laser intensity sufficient for an assumed two-photon absorption process. Core stress changes indicate a contribution of compaction to the index changes.

2. Experiment

The fiber preform had a core /cladding ratio of 0.23 and a core-cladding index difference of $\Delta n = 4.85\times10^{-3}$, which corresponds to ≅ 3.3 mol% GeO_2. Fig. 1 shows the refractive index profile of the fiber preform. Clearly observable are the different ring sections and the dip at the core center. From the preform fibers have been drawn with 50±0.7 and 40 ± 0.7 μm external diameter corresponding to 11.6 and 9.3 μm core size. A cw Ar^+ laser operating at 244 nm with a Gaussian beam profile and a $1/e^2$ beam size of 0.7 mm was used for fiber Bragg grating (FBG) inscription in the fibers that have not been hydrogen loaded before (pristine fibers) and which were of low germanium concentration. The beam was focused using a cylindrical lens (f = 102 mm) perpendicular to the fiber axis to a $1/e^2$ beam size of ~82 μm. The laser output power was varied from 30 to 100 mW. The intensity is estimated to range between 50 and 174 W/cm^2 for the gratings fabricated with different intensity. Grating reflection spectra were monitored during irradiation to obtain the mean index change. At the end of the irradiation UV-induced stress changes have been measured using a polarimetric method by comparing the FBG center with the un-irradiated fiber section [8].

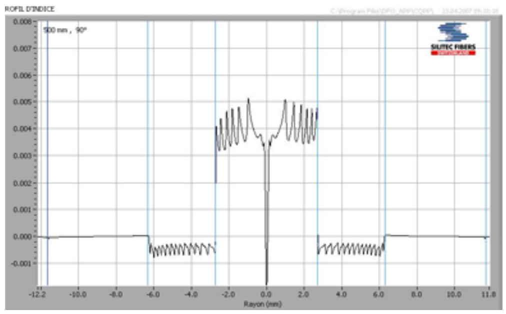

Fig 1. Refractive index profile of fiber preform.

3. Results and discussion

Figure 2 shows the reflection spectrum of the FBG fabricated with 104 W/cm^2 in 3.3 mol% fiber at the end of the irradiation corresponding to a total dose of 401 kJ/cm^2. From a transmission measurement the reflectivity is ~10 %. Assuming a Gaussian apodization for the refractive index profile with a FWHM grating length of 0.6 mm (corresponding to a 1/e^2 beam size of 0.7 mm), a value of 0.77 for the overlap integral, the refractive index modulation amplitude is 5.9×10^{-4}. The corresponding mean index change is 6.7×10^{-4}. The mean index changes have been measured from the Bragg wavelength shift and are shown in Fig. 3 as a function of exposure time for 4 different laser intensities. The index changes are very steep in the beginning followed by a slow growth with higher exposure. For the intensity of 174 W/cm^2 a maximum mean index change of 1.56×10^{-3} was reached. This value is even higher than the value obtained by the author using a pulsed 240 nm dye laser in a standard telecom fiber [7]. It is interesting to note that quite high index changes are obtained within the first 60 seconds. The spectra acquisition rate was too small to get the initial slope, $d\Delta n/dt$. Nevertheless, the data suggest a two-photon behavior; a fact that has to be confirmed by additional experiments.

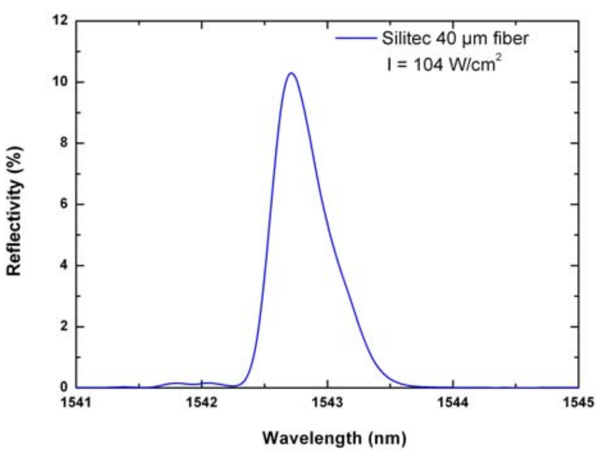

Fig. 2 Reflection spectrum of 0.6-mm-long FBG fabricated in low GeO_2 doped (3.3 mol%) fiber using a cw-Ar+ laser (244 nm).

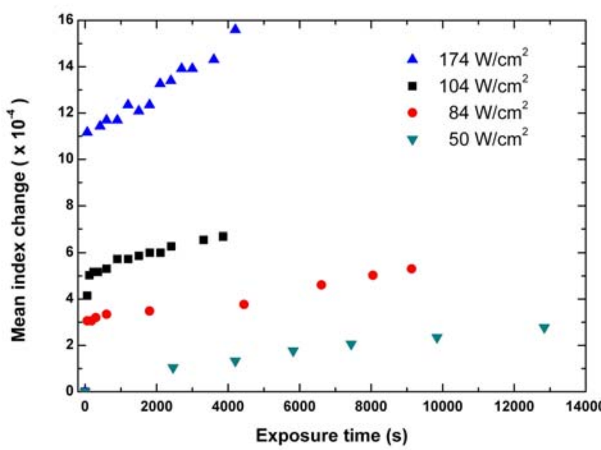

Fig. 3 FBG index changes as a function of irradiation time for different intensities.

Stress measurements have been performed in the pristine and the irradiated fiber. Care was taken to identify the maximum of the UV-irradiated zone as the laser beam has a Gaussian profile. The stress data are averaged over a longitudinal distance of typically 0.25 mm, i.e. 1024 lines of the CCD camera. The axial stress data were almost constant over this section. Figure 4 shows the elastic stress profiles of fiber sections corresponding to the pristine and the fiber irradiated with a total dose of 401 kJ/cm^2. As the measured birefringence is a superposition of elastic stress and drawing induced inelastic strain birefringence both contributions have been separated assuming an inelastic strain constant over the fiber section and an area integral over the elastic stress that is zero [8]. The inelastic strain that is proportional to the drawing force is in fact very low (corresponds to 0.2 ± 0.1 MPa) as the fiber has been drawn with a very low drawing tension and does not change due to irradiation. As the inelastic strain can be annealed, but is still present in the UV-irradiated fiber it is concluded that the temperature during irradiation stayed well below the melting temperature. The spectrum of axial elastic stress is composed of a core, an inner cladding region and a cladding tube. The axial core stress is positive due to the higher thermal expansion coefficient of GeO_2 and the small drawing tension. The axial core stress increases due to UV irradiation. The stress averaged over the fiber core changes from 14.6 to 49.7 MPa for a mean index change of 6.7×10^{-4}. As the core is attached to the cladding an increase in core stress is due to a compaction of the irradiated GeO_2-doped core. The ratio of stress changes to total index changes (52.4 GPa) is smaller than the value obtained for fibers of different GeO_2 concentration irradiated by 244 nm dye laser [9], or 800 nm-irradiated SMF-28 [10] [11].

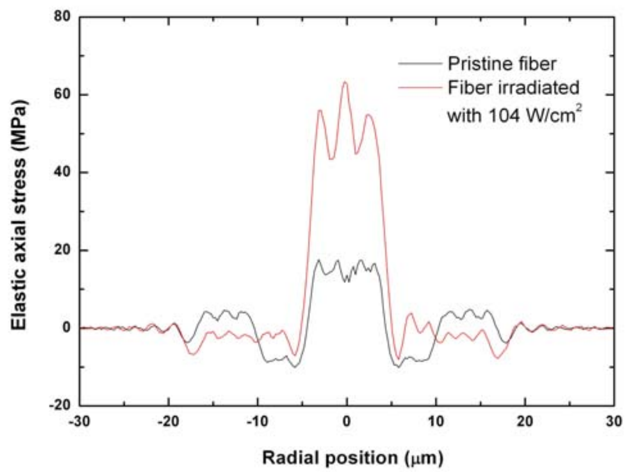

Fig. Axial stress in the FBG before and after cw-UV-irradiation at 244 nm and a total dose of 401 kJ/cm^2.

3. Conclusions

In conclusion it was shown that it is possible to fabricate FBG in 40 μm optical fibers with a germanium concentration (3.3 mol%) similar to a standard telecom fiber using cw-244 nm Ar^+ laser without hydrogen loading. Mean index changes as high as 1.1×10^{-3} have been achieved after 60 seconds of irradiation. The initial index change depends strongly on the laser intensity. Positive stress changes indicate a compaction contribution to the total index change.

4. References

1. K. Satori, Y. Ikeda, Y. Kurosawa, A. Hongo, and N. Takeda, "Development of small-diameter optical fiber sensors for damage detection in composite laminates," Proc. Proceedings of SPIE - Smart Structures and Materials: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials **3986**, 104-111, Newport Beach, CA, USA, (2000).
2. S. Kojima, S. Komatsuzaki, Y. Kurosawa, and A. Hongo, "Embedding type strain sensors using small-diameter fiber Bragg grating to composite laminate structures," Hitachi Cable Review **23**, 11-15 (2004).
3. R. M. Atkins, P. J. Lemaire, T. Erdogan, and V. Mizrahi, "Mechanisms of enhanced UV photosensitivity via hydrogen loading in germanosilicate glasses," Electronics Letters **29**, 1234-1235(1993).
4. P. J. Lemaire, R. M. Atkins, V. Mizrahi, and W. A. Reed, "High Pressure H2 loading as a technique for achieving ultrahigh UV photosenitivity and thermal sensitivity in GeO2 doped optical fibres," Electronics Letters **29**, 1191-1193 (1993).
5. P. L. Swart, M. G. Shlyagin, A. A. Chtcherbakov, and V. V. Spirin, "Photosensitivity measurement in optical fibre with Bragg grating interferometers," Electronics Letters **38**, 1508-1509 (2002).
6. D. L. Williams, B. J. Ainslie, J. R. Armitage, R. Kashyap, and R. Campbell, "Enhanced UV Photosensitivity in Boron Codoped Germanosilicate Fibers," Electronics Letters **29**, 45-47 (1993).
7. H. G. Limberger, P. Y. Fonjallaz, and R. P. Salathé, "Spectral Characterization of Photoinduced High Efficient Bragg Gratings in Standard Telecommunication Fibers," Electronics Letters **29**, 47-48 (1993).
8. F. Dürr, H. G. Limberger, R. P. Salathé, and A. D. Yablon, "Inelastic Strain Birefringence in Optical Fibers," Proc. Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference on CD-ROM, OWA 2, Annaheim, (2006).
9. P. Y. Fonjallaz, H. G. Limberger, R. P. Salathé, F. Cochet, and B. Leuenberger, "Tension increase correlated to refractive index change in fibers containing UV-written Bragg gratings," Optics Letters **20**, 1346-1348 (1995).
10. F. Dürr, H. G. Limberger, R. P. Salathé, F. Hindle, M. Douay, E. Fertein, and C. Przygodzki, "Tomographic measurement of femtosecond-laser induced stress changes in optical fibers," Applied Physics Letters **84**, 4983-4985 (2004).
11. H. G. Limberger, C. Ban, R. P. Salathé, S. A. Slattery, and D. N. Nikogosyan, "Absence of UV-induced stress in Bragg gratings recorded by high-intensity 264 nm laser pulses in a hydrogenated standard telecom fiber," Optics Express **15**, 5610-5615 (2007).