Photosensitivity and stress changes of Ge-free Bi-Al doped silica optical fibers under ArF excimer laser irradiation

Christian Ban,[1] Hans G. Limberger,[1,*] Valery Mashinsky,[2] and Evgeny Dianov[2]

[1] *Ecole Polytechnique Fédérale de Lausanne (EPFL), School of Engineering (STI), CH-1015 Lausanne, Switzerland*
[2] *Fiber Optics Research Center RAS, 38 Vavilov Street, 119333 Moscow, Russia*
[*] *hans.limberger@epfl.ch*

Abstract: The photosensitivity of germanium free Bi-Al-doped silica fibers with different bismuth concentrations was investigated using ArF excimer laser radiation at 193 nm and fiber grating formation. For the fiber with the highest bismuth concentration maximum refractive index changes of 2.2×10^{-3} and 2.0×10^{-4} were obtained for hydrogen loaded and unloaded fibers, respectively. Irradiation induced tensile stress changes were observed in the fiber core of H_2-loaded and unloaded fibers. The results indicate a contribution of compaction to the total refractive index change in both cases.

OCIS codes: (060.3738) Fiber Bragg gratings, photosensitivity; (060.3510) Lasers, fiber.

References and links

1. K. Murata, Y. Fujimoto, T. Kanabe, H. Fujita, and M. Nakatsuka, "Bi-doped SiO_2 as a new laser material for an intense laser," Fusion Eng. Des. **44**(1-4), 437–439 (1999).
2. Y. Fujimoto and M. Nakatsuka, "Infrared luminescence from bismuth-doped silica glass," Jpn. J. Appl. Phys. Part 2 **40**(3B), 279–281 (2001).
3. T. Suzuki and Y. Ohishi, "Ultrabroadband near-infrared emission from Bi-doped Li_2O-Al_2O_3-SiO_2 glass," Appl. Phys. Lett. **88**(19), 191912 (2006).
4. Y. Fujimoto and M. Nakatsuka, "Optical amplification in bismuth-doped silica glass," Appl. Phys. Lett. **82**(19), 3325–3326 (2003).
5. T. Haruna, M. Kakui, T. Taru, S. Ishikawa, and M. Onishi, "Silica-based bismuth-doped fiber for ultrabroad band light-source and optical amplification around 1.1 µm," in *Optical Amplifiers and Their Applications Topical Meeting (OAA)*, (OSA, 2005), MC3.
6. V. V. Dvoyrin, V. M. Mashinsky, E. M. Dianov, A. A. Umnikov, M. V. Yashkov, and A. N. Guryanov, "Absorption, fluorescence and optical amplification in MCVD bismuth-doped silica glass optical fibres," in *ECOC 2005 – 31st European Conference and Exhibition on Optical Communication*, (IEE, 2005), Th3.3.5.
7. V. V. Dvoyrin, O. I. Medvedkov, V. M. Mashinsky, A. A. Umnikov, A. N. Guryanov, and E. M. Dianov, "Optical amplification in 1430-1495 nm range and laser action in Bi-doped fibers," Opt. Express **16**(21), 16971–16976 (2008).
8. E. M. Dianov, V. V. Dvoyrin, V. M. Mashinsky, A. A. Umnikov, M. V. Yashkov, and A. N. Gur'yanov, "CW bismuth fibre laser," Quantum Electron. **35**(12), 1083–1084 (2005).
9. A. B. Rulkov, A. A. Ferin, S. V. Popov, J. R. Taylor, I. Razdobreev, L. Bigot, and G. Bouwmans, "Narrow-line, 1178 nm CW bismuth-doped fiber laser with 6.4 W output for direct frequency doubling," Opt. Express **15**(9), 5473–5476 (2007).
10. I. Razdobreev, L. Bigot, V. Pureur, A. Favre, G. Bouwmans, and M. Douay, "Efficient all-fiber bismuth-doped laser," Appl. Phys. Lett. **90**(3), 031103 (2007).
11. Z. Yang, Q. Zhang, and Z. Jiang, "Photo-induced refractive index change of bismuth-based silicate glass," J. Phys. D **38**(9), 1461–1463 (2005).
12. H. G. Limberger, P. Y. Fonjallaz, R. P. Salathé, and F. Cochet, "Compaction- and photoelastic- induced index changes in fiber Bragg gratings," Appl. Phys. Lett. **68**(22), 3069–3071 (1996).
13. 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," Opt. Lett. **20**(11), 1346–1348 (1995).
14. 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," Appl. Phys. Lett. **84**(24), 4983–4985 (2004).
15. 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," Opt. Express **15**(9), 5610–5615 (2007).

#157211 - $15.00 USD Received 28 Oct 2011; revised 5 Dec 2011; accepted 5 Dec 2011; published 15 Dec 2011

16. H. G. Limberger and G. Violakis, "Formation of Bragg gratings in pristine SMF-28e fibre using cw 244-nm Ar^+-laser," Electron. Lett. **46**(5), 363–365 (2010).
17. F. Dürr, "Laser-Induced Stress Changes in Optical Fibers," PhD thesis no. 3314 (Swiss Federal Institute of Technology, Lausanne, 2005).
18. J. Albert, M. Fokine, and W. Margulis, "Grating formation in pure silica-core fibers," Opt. Lett. **27**(10), 809–811 (2002).
19. B. Malo, J. Albert, K. O. Hill, F. Bilodeau, D. C. Johnson, and S. Theriault, "Enhanced photosensitivity in lightly doped standard telecommunication fiber exposed to high fluence ArF excimer-laser light," Electron. Lett. **31**(11), 879–880 (1995).
20. I. Riant and F. Haller, "Study of the Photosensitivity at 193 nm and Comparison with Photosensitivity at 240 nm Influence of Fiber Tension: Type IIA Aging," J. Lightwave Technol. **15**(8), 1464–1469 (1997).
21. J. Albert, B. Malo, K. O. Hill, F. Bilodeau, D. C. Johnson, and S. Theriault, "Comparison of one-photon and two-photon effects in the photosensitivity of germanium-doped silica optical fibers exposed to intense ArF excimer laser pulses," Appl. Phys. Lett. **67**(24), 3529–3531 (1995).
22. C. Ban, H. G. Limberger, V. M. Mashinsky, V. V. Dvoyrin, L. I. Bulatov, and E. M. Dianov, "ArF excimer laser induced refractive index changes in Bi-Al-doped silica optical fiber," in *LPHYS'08: 17th International Laser Physics workshop*, 2008).
23. C. Ban, H. G. Limberger, V. M. Mashinsky, V. V. Dvoyrin, L. I. Bulatov, and E. M. Dianov, "Photosensitivity of Bi-Al-doped silica optical fibers to 193 nm excimer laser irradiation," in *3rd European Physical Society - Quantum Electronics and Optics Division Europhoton Conference on "Solid-state and fiber coherent light sources"* (2008).
24. C. Ban, H. G. Limberger, V. Mashinsky, V. Dvoyrin, and E. Dianov, "UV-Photosensitivity of Germanium-free Bi-Al Silica Fibers," in *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides BGPP: OSA Topical Meeting*, (OSA, 2010), BWD3.
25. V. V. Dvoyrin, V. M. Mashinsky, L. I. Bulatov, I. A. Bufetov, A. V. Shubin, M. A. Melkumov, E. F. Kustov, E. M. Dianov, A. A. Umnikov, V. F. Khopin, M. V. Yashkov, and A. N. Guryanov, "Bismuth-doped-glass optical fibers—a new active medium for lasers and amplifiers," Opt. Lett. **31**(20), 2966–2968 (2006).
26. P. L. Chu and T. Whitbread, "Measurement of stresses in optical fiber and preform," Appl. Opt. **21**(23), 4241–4245 (1982).
27. A. D. Yablon, "Optical and mechanical effects of frozen-in stresses and strains in optical fibers," IEEE J. Sel. Top. Quantum Electron. **10**(2), 300–311 (2004).
28. F. Dürr, H. G. Limberger, R. P. Salathé, and A. D. Yablon, "Inelastic Strain Birefringence in Optical Fibers," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference on CD-ROM (OSA 2006)* (2006), OWA 2.
29. W. Primak and D. Post, "Photoelastic constants of vitreous silica and its elastic coefficient of refractive index," J. Appl. Phys. **30**(5), 779–788 (1959).
30. W. Hermann, M. Hutjens, and D. U. Wiechert, "Stress in optical waveguides. 3: Stress induced index change," Appl. Opt. **28**(11), 1980–1983 (1989).
31. Y. Larionov, A. Rybaltovsky, S. Semjonov, M. Bubnov, E. Dianov, S. Vartapetov, M. Kurzanov, A. Obidin, V. Yamschikov, A. N. Guryanov, M. V. Yashkov, and A. A. Umnikov, "High photosensitivity of Al_2O_3-doped fibers to 193 nm and 157 nm excimer laser irradiation," in *Bragg Gratings Photosensitivity and Poling in Glass Waveguides*, 2003), 46–48.

1. Introduction

Optical fiber materials with broad-band gain in the visible or in the telecommunication window are of great interest for optical communication and the biomedical domain in order to build integrated tunable lasers, amplifiers, ultra-short pulse lasers, or broadband light sources. In particular, as no active fiber for the second telecommunication window (around 1310 nm) is compatible with common silica-based telecommunication fibers, broadband light sources emitting in this wavelength region are of great importance.

Bismuth ions are interesting candidates for *near infrared (NIR) luminescence* in silica glass [1–4] and in silica optical fibers [5–7]. NIR-luminescence was first reported by Murata and Fujimoto et al. for aluminosilicate *glass* at room temperature [1,2]. Up to 500 nm of full width at half maximum (FWHM) spectral bandwidth at 1200 nm was detected under 900-nm excitation [3]. Also amplification at 1.3 μm was demonstrated in Bi-Al doped silica glass [4]. In aluminum co-doped silica optical fibers *room temperature luminescence* of bismuth was first published in 2005 by Haruna et al. [5] and Dvoyrin et al. [6]. The luminescence was observed around 750 and 1100 nm under visible light pumping, and at 1150 nm under 1000 nm pumping [6] with a spectral bandwidth of 150–300 nm. Later, luminescence was also obtained at 1430 nm under 1343 nm pumping in Bi-Al-doped silica fiber [7].

All-fiber lasers were first realized using the strong luminescence band around 1150 nm [8] and recently using the weak band at 1400 nm in germanium free Bi-Al-silica doped fibers [7].

#157211 - $15.00 USD Received 28 Oct 2011; revised 5 Dec 2011; accepted 5 Dec 2011; published 15 Dec 2011

The all-fiber lasers contained fiber Bragg gratings (FBG) written in Ge-doped fibers as laser mirrors so far [7–10]. Inscription of FBG directly into the active fiber would reduce the loss due to splicing and mode field mismatch leading to higher laser efficiency.

Photosensitivity of bismuth-silicate glass was detected using 248-nm excimer laser irradiation of 30 mJ/cm^2 pulse fluence with refractive index changes up to 2.1×10^{-4} at 1550 nm [11]. The conjecture was that the photosensitivity was due to volume changes in the Bi-doped glass. The physical mechanisms responsible for the photosensitivity of germanosilicate glass have been assigned to *color-center changes*, *compaction* of the glass network, and *stress changes* [12]. Strong tension increase that correlates linearly with refractive index changes was demonstrated in germanosilicate fiber cores irradiated by UV laser light [12,13]. Recently, we confirmed similar positive core stress changes in SMF-28 fiber using 800-nm [14] and 264-nm femtosecond [15], as well as cw-Ar^+-244-nm laser light [16]. The increase in tension lowers the refractive index through the photoelastic effect. The tension increase is caused by the *compaction* of the irradiated fiber core [12] which itself leads to a positive refractive index (RI) change that exceeds the negative photoelastic effect [17]. The net refractive index change is positive. In addition, color center changes add to the total refractive index change. Recently, Limberger et al. reported that for 264-nm femtosecond laser irradiation of H_2-loaded fibers no stress change was observed for moderate total dose indicating the absence of compaction. In this case the origin of refractive index changes was attributed to color centers only [15].

As the bismuth fibers are germanium free an ArF excimer laser operating at 193 nm was used to induce refractive index changes. Fibers without germanium, e.g. pure silica fibers are known to have very low photosensitivity. Using an ArF laser refractive index changes of 1×10^{-5} and 5×10^{-5} [18] were achieved with about 25 kJ/cm^2 of cumulated fluence in pristine and D_2-loaded pure silica fibers, respectively. Germanium doping increases the photosensitivity, which was observed to depend on fluence per pulse, H_2-loading, and on germanium concentration [19–21]: A two-photon process in pristine low GeO_2 doped fibers (3 mol%, SMF-28) [19], and a one-photon process in such fibers but H_2-loaded [20] as well as in high (8 mol%) GeO_2 doped fibers [21].

So far we published only short conference abstracts and reports on ArF photosensitivity of germanium free bismuth doped aluminosilicate fibers [22–24]. Here we report in more detail on refractive index and stress changes in hydrogen loaded and un-loaded fibers and compare their photosensitivity to standard SMF-28 fibers using 193-nm excimer irradiation.

2. Experiment

The photosensitivity of three Bi-doped fibers (#5, #10, and #25) with different Bi-concentrations was investigated. The Bi-Al fibers have an SiO_2 cladding and an Bi-Al-doped silica core. Preform #5 was prepared using a solution doping technique, while the modified chemical vapor deposition technique was used for preforms #10 and #25. The bismuth concentration was 0.15-0.3 at.% for fiber #5 and <0.02 at.% for fibers #10 and #25. Aluminum was incorporated as a dopant in the preforms to provide NIR-Bi-luminescence (1-1.3 µm spectral range) and to raise the core refractive index. The cutoff wavelength estimated from the core size and the refractive index difference between core and cladding range from 0.95 to 1.35 µm (with an error of 10%). For comparison, the standard telecom SMF-28 fiber (~3 mol% GeO_2) was irradiated and results included. Table 1 shows the main Bi-fiber parameters. Hydrogen loading at a pressure of typically 150 bar at room temperature for 2 weeks was used to increase UV photosensitivity. The total Bi-concentration of 2 fibers (#10, #25) was below the detection limit (0.02 at%) of the scanning electron microscope energy-dispersive x-ray analyzer [25]. Since the loss at 1 µm can be attributed to the Bi-active centers, this loss was used as an indication for their concentration. The Bi-active-center concentration increased in sample order Bi#25, Bi#10, then Bi#5.

Fiber Bragg gratings of $L = 6$ mm length have been recorded using 193 nm ArF excimer laser with a repetition rate of 10 Hz and a phase mask. The laser beam was focused by a fused silica cylindrical lens of 20 cm focal length through a phase mask onto the fiber (mask period:

#157211 - $15.00 USD Received 28 Oct 2011; revised 5 Dec 2011; accepted 5 Dec 2011; published 15 Dec 2011

$\Lambda = 1.074\ \mu m$, zero order ≈4%, Bragg wavelength λ_B ≈1.55 µm). The spot size at the fiber position was estimated to 6 × 3.2 mm^2 and the fluence per pulse, F_p, was typically 100 - 200 mJ/cm^2. Reflection and transmission measurements were performed during irradiation using a commercial tunable fiber laser. The refractive index amplitude Δn_{ac} was acquired from the maximum $R_{\max}$ in the reflection spectra using: $\Delta n_{ac} = \Delta n_{ac}^{eff} \cdot \eta^{-1} = \lambda_B \cdot (\eta \cdot \pi \cdot L)^{-1} \cdot \text{artanh}\sqrt{R_{\max}}$. The mean refractive index change Δn_{dc} was obtained from the Bragg wavelength shift as $\Delta n_{dc} = \Delta n_{dc}^{eff} \cdot \eta^{-1} = n_{eff} \cdot \Delta\lambda_B \cdot (\eta \cdot \lambda_B)^{-1}$. The overlap integral η was considered to be constant except for the case where the fibers were far from LP_{11}-cutoff (Bi#10).

Table 1. Properties of Bismuth Doped Silica Optical Fibers

Sample	Core glass composition		Bismuth	Core size	Cut-off wavelength	Loss at 1 µm	Overlap integral
	SiO_2	Al_2O_3	concentration				η
	(mol.%)	(mol.%)	(at.%)	(µm)	(µm)	(dB/m)	
#5	96.7	3.3	0.15-0.3	6.9	1.35	≈20	0.74
#10	98	2	< 0.02	6.7	0.95	2.0	0.60
#25	98	2	< 0.02	8.8	1.25	1.06	0.74

Stress measurements were performed on pristine, irradiated, H_2-loaded, and irradiated H_2-loaded fibers using the set-up described in Ref [17]. Before the stress measurements, the fibers were annealed at 100°C for 36 h to ensure hydrogen out diffusion. Using the 10 × objective the spatial resolution is estimated to 0.7 µm at 632.8 nm. The birefringence induced retardation is integrated perpendicular to the fiber axis and along the axis of the fiber probing beam as a function of the lateral coordinate *y*. The retardation values were averaged over a range of 400 µm along the fiber axis to improve the signal to noise ratio. The measured retardation is a superposition of elastic stress birefringence [26] and drawing induced inelastic strain birefringence [27]. The inelastic strain is basically influenced by the material with the higher viscosity, as it solidifies first during fiber drawing and takes over the drawing force. In silica based fibers the material with the higher viscosity is in general the cladding. Both contributions can be separated assuming an inelastic strain that is constant over the fiber cross section, *A*, and an area integral over the elastic stress that is zero according to *St. Venants* principle [28]. From the retardation profile, $\Re^{\text{tot}}(y)$, the axial elastic stress $\sigma_z(r)$ is calculated by:

$$\sigma_z(r) = I(r) - I_n \tag{2}$$

where

$$I(r) = -\frac{1}{\pi C}\int_r^R \frac{d\Re^{\text{tot}}(y)/dy}{\sqrt{y^2 - r^2}}\,dy \tag{3}$$

is the Abel integral of the measured retardation [26], *R* is the fiber radius, *r* and *y* are radial and Cartesian coordinates, and *C* is the silica stress optic constant (see Table 2) [29]. The normalized stress integral I_n is given by the non-vanishing part of the area integral normalized to the fiber cross section: $I_n = \int_A I(r)\,dA \Big/ \int_A dA$. The inelastic strain, $\Delta\varepsilon$, is calculated as

$$\Delta\varepsilon = \frac{(1+\nu)}{E} I_n \tag{4}$$

#157211 - $15.00 USD Received 28 Oct 2011; revised 5 Dec 2011; accepted 5 Dec 2011; published 15 Dec 2011

where E and ν are *Young's* modulus and *Poisson's* ratio. It was demonstrated that the inelastic strain is proportional to the fiber drawing tension [28].

Table 2. Photoelastic Constants of Vitreous Silica at 546 nm [29]

Extra ordinary ray	C_1	TPa^{-1} (Brewster)	0.64
Ordinary ray	C_2	TPa^{-1}	4.22
Stress optical constant	$C = C_2 - C_1$	TPa^{-1}	3.57

The photoelastic core refractive index change is calculated from the core stress changes by [30]:

$$\Delta n^{pe} = -\left(C_1 + 3C_2\right)\Delta\sigma_z^{core}/2 \tag{5}$$

where C_1 and C_2 are the photoelastic constants of the extraordinary and ordinary ray [29].

3. Results and discussion

3.1 Photosensitivity

Figure 1(a) shows the mean refractive index change versus exposure dose for *unloaded* fibers Bi#5, #10, #25, and SMF-28. An effective group index of 1.446 was measured for all Bi-fibers from the Bragg wavelength detected with the first pulse. The refractive index changes of the three Bi-doped fibers were lower than that of the SMF-28 reference fiber. The mean refractive index change increases slightly with bismuth concentration. The fiber with the highest bismuth concentration (Bi#5) exhibited the highest mean refractive index change of 2.0×10^{-4}. Lower fluence per pulse led to smaller refractive index changes (inset Fig. 1(a)). As the photosensitivity increased with bismuth concentration, the photosensitivity is most probably related to bismuth in pristine Bi-Al-silica fibers. Moreover, the RI change in Bi-Al fibers induced by ArF excimer laser light is also much larger than the RI change in pure silica core fibers where a value of $\approx 6 \times 10^{-6}$ was reported for a comparable dose of ≈ 6 kJ/cm^2 [18].

The Bi-Al-doped fibers were hydrogen loaded and subsequently irradiated (Fig. 1(b)). A mean refractive index change up to $\Delta n_{dc} = 2.2 \times 10^{-3}$ was attained for the Bi-doped fiber with the highest concentration (#5) which is about 40% of the SMF-28-value and twice the value obtained for the Bi fibers with lower concentrations (Bi#10, Bi#25). The observed RI change in Bi#5 is about two orders of magnitude higher than values reported for deuterium loaded pure silica fiber using an ArF excimer laser ($\approx 2 \times 10^{-5}$) with 6 kJ/cm^2 of total dose [18]. Refractive index changes have been reported for H_2-loaded Al-doped silica fiber under ArF irradiation (200 mJ/cm^2) [31]. The Bi#10 has about the same dose dependence as the Al-SiO_2 fiber, but the fiber with the highest Bi-concentration (Bi#5) shows clearly higher index changes. Therefore, the photosensitivity observed in H_2-loaded Bi-doped fibers might be attributed to Bi-H species (BiH, BiOH, ...). The refractive index changes were found to be sufficient to directly inscribe high reflective FBG into the H_2-loaded bismuth-doped fibers to be used as laser mirrors: In a 6-mm-long FBG a reflectivity of R = 99.7% (–25.4 dB transmission dip, $\Delta n_{ac} = 4.5 \times 10^{-4}$) was achieved in hydrogen loaded Bi#10.

#157211 - $15.00 USD Received 28 Oct 2011; revised 5 Dec 2011; accepted 5 Dec 2011; published 15 Dec 2011

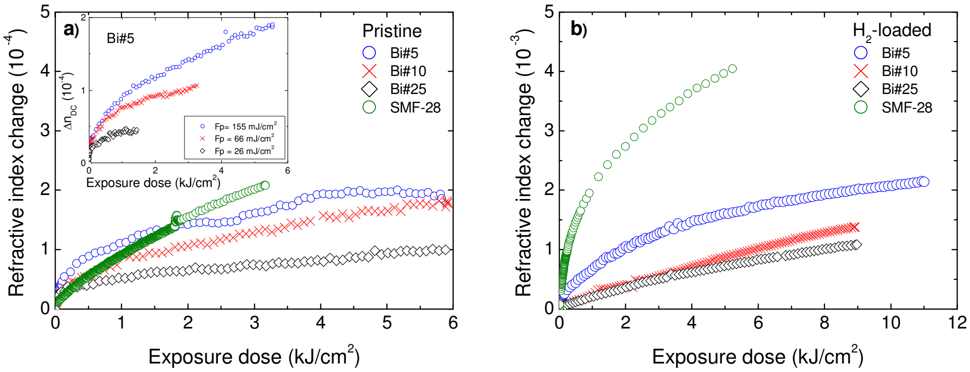

Fig. 1. Mean refractive index change versus dose in (a) pristine (F_p = 160 mJ/cm^2) and in (b) H_2-loaded Bi-Al-doped fibers (F_p = 135 mJ/cm^2). Inset in (a) shows the dependence on exposure for different F_p.

3.2 Stress, inelastic strain measurements

The tomographic measurements revealed symmetric stress distributions in spite of asymmetrical (one-sided) 193 nm irradiation. Figures 2(a) and 2(b) show the 1-dimensional axial stress distribution of unloaded and H_2-loaded fiber Bi#10 before (blue curve) and after irradiation (red), respectively. The core region of *pristine* Bi#10 has an average axial stress of −3.4 MPa. An UV-induced axial stress increase of 15 ± 3 MPa occurred in the core. The corresponding photoelastic index change is $\Delta n^{pe} = -1.0\times10^{-4}$, calculated using Eq. (5). The negative photoelastic index change is compensated by a positive compaction induced index change. Compaction, photoelastic, and color center induced index changes result in the total mean refractive index change of $\Delta n_{dc} = 1.3 \times 10^{-4}$ measured by the FBG peak shift.

No stress changes due to H_2-loading were observed. For a UV-induced refractive index change of $\Delta n_{dc} = 1.2 \times 10^{-3}$ the stress changed in the core region by 32 ± 3 MPa which corresponds to a photoelastic index change of $\Delta n^{pe} = -2.1\times10^{-4}$. The stress distribution in the core region revealed a pronounced dip in the center of the core similar to the Bi-dopant profile of the fiber preform (see Fig. 1 in Ref [25]). While the aluminum concentration is uniform across the preform core, the bismuth concentration is reduced at the center as a result of the fabrication process. This is an indication that the photo-induced stress, and hence the photosensitivity is directly connected to the Bi species.

In general, it is assumed that H_2-loading leads to a color center based refractive index change with the absence of stress changes [15]. However, in this fiber, core stress changes and corresponding compaction of the fiber core occurred after a long exposure time. This indicates that in H_2-loaded fibers core volume changes may appear as well. The UV-induced stress change per total index change, $\Delta\sigma_{core}\cdot\Delta n_{tot}^{-1}$, is 23 GPa and ~106 GPa for the H_2- and the non-H_2-loaded Bi#10 fiber. For comparison, in Ref [13] 119 GPa were observed for different Ge-doped fibers. Although the stress change per total index change in the H_2-loaded case was only about 1/5 of the unloaded value it is the first time that non-zero stress changes were detected in H_2-loaded fibers.

The normalized stress integral I_n was constant with 0.8 ± 0.2 MPa for all cases corresponding to an inelastic strain of 1.3×10^{-5}. Silica fibers have an inelastic strain per drawing tension of typically 7.75×10^{-7} g^{-1}, which gives a small drawing tension of 17 ± 4 g. This value correlates well with experimental value of fiber drawing force which was estimated to 25 ± 5 g.

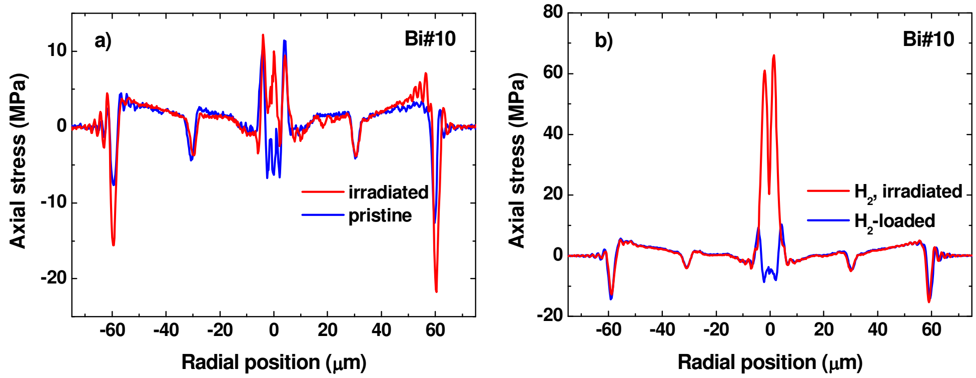

Fig. 2. Axial stress profiles before (blue) and after UV-irradiation ($\Delta n_{dc} = 1.3 \times 10^{-4}$, red) in pristine Bi-Al silica (a) and in H_2-loaded Bi-Al silica fiber ($\Delta n_{dc} = 1.2 \times 10^{-3}$, red) (b).

4. Conclusion

The photosensitivity of Bi-Al-doped silica fibers was investigated by FBG fabrication and stress measurements using an ArF excimer laser. The refractive index change increases with Bi-concentration and laser pulse fluence. The achieved value of 2×10^{-4} in pristine fiber is below the value for SMF-28. A maximum mean refractive index change of 2.2×10^{-3} was attained for hydrogen loaded Bi-Al fibers. This is about 40% of the value obtained for H_2-loaded SMF-28, and 2 times higher than values reported for Al-SiO_2 fibers. The increase of UV-induced refractive index change with Bi-concentration and the similarity of the induced stress distribution in the H_2-loaded fiber with the Bi-dopant profile indicate that the photosensitivity is most probably due to bismuth. For hydrogen loaded Bi-Al-silica fibers the photosensitivity is attributed in a great part to Bi-H species. Irradiation induced tensile stress changes that can be related to volume changes were observed for both the unloaded and for the first time for the H_2-loaded silica fiber. Inelastic strains were small and remained constant.

Acknowledgments

The authors thank Dr. A. A. Umnikov, Prof. A. N. Guryanov and N. N. Vechkanov (Institute of Chemistry of High-Purity Substances of the Russian Academy of Sciences) for the fibers fabrication. Financial support from the Swiss National Science Foundation (project 200020-116216) is acknowledged.

#157211 - $15.00 USD Received 28 Oct 2011; revised 5 Dec 2011; accepted 5 Dec 2011; published 15 Dec 2011