Absence of UV-induced stress in Bragg gratings recorded by high-intensity 264 nm laser pulses in a hydrogenated standard telecom fiber

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Abstract: We report on photochemical two-photon Bragg grating preparation in hydrogenated fiber without any UV-induced stress in the core or cladding, leaving only the color-center model responsible for refractive index changes for UV femtosecond irradiation. Without hydrogen loading strong stress changes are observed in the core and in the cladding indicating glass compaction. The irradiation does not change the inelastic strains, in contrast to H_2-loading.

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1. Introduction

The physical mechanisms responsible for the photosensitivity of germanosilicate glass have been actively studied since the invention of fiber Bragg gratings (FBGs). The *color-center model* [1], proposed in 1990, considers that UV exposure of the 5.12 eV band of germanium oxygen-deficient centers brings about the release of photoelectrons, which become trapped in neighboring sites, thus creating new color centers. The following modification of the UV absorption spectrum of the germanosilicate glass leads to a refractive index modification at longer wavelengths. This model underestimated the value of the induced index changes. The *compaction model* proposed by Bernardin and Lavandy [2] at about the same time considers a two photon activated Ge-Si bond breakage that leads to the compaction of the glass network. Their suggestion was based on the work of Fiori et al. who reported on UV induced linear compaction in fused silica slab waveguides that leads to positive refractive index changes [3]. Glass compaction was thought to occur via the collapse of higher order ring structures into 2- or 3-membered rings. Changes in the Raman spectra of UV irradiated fibers indicating a reduction of higher order Si-O-Si(Ge)-O- rings and the increase of low-fold (2-4) rings under UV irradiation were later reported by Dianov et al. [4]. In 1995 a strong tension increase was observed in a germanosilicate fiber core irradiated by UV laser light [5, 6] that was linearly proportional to the refractive index modulation. Recently, we reported on similar positive core stress changes in a SMF-28 fiber induced by 800-nm femtosecond laser light [7]. Although it is known that an increase in tension lowers the refractive index through the photoelastic effect, nevertheless, only an overall positive index change can be responsible for the index changes observed after FBG inscription. As *compaction* leads to a tension increase in the core it was considered as an important component of fiber photosensitivity [6]. The UV-induced increase of the refractive index in the fiber core, due to both *color-center* and *compaction* effects, exceeds the decrease caused by the photo-elastic effect. The amount of each contribution might vary strongly as a function of fiber content, pre-irradiation treatment and irradiation wavelength.

Recently, the two-photon UV approach to FBG inscription was proposed and developed [8-11]. This method utilizes high-intensity (~100 GW/cm^2) 264 (or 267) nm femtosecond

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pulses for FBG inscription in low-UV-absorbing telecom [8-10], silica-core [10] and holey fibers [11]. This approach, based on two-photon absorption [12, 13], which means *the simultaneous* absorption of two light quanta through an *intermediate virtual state*, is different from the two-step excitation [14], which also involves the absorption of two light quanta, but in *two consecutive elementary acts*, including the absorption of the second photon *during the lifetime of the intermediate real state*. It was shown [15] that such two-step excitation (also known as biphotonic) needs a significant linear absorption as well as absorption from the excited states and proceeds at much lower intensities, i.e. at about 10 MW/cm^2 in the case of a germanosilicate fiber core, exposed to 193 nm. Zagorulko et al. have shown [10] that hydrogen loading of a standard telecom SMF-28 fiber brings about a substantial decrease in the UV irradiation fluence value necessary for two-photon FBG recording, which is in line with the use of hydrogenation for pre-irradiation treatment of germanosilicate fibers in the conventional low-intensity single-quantum inscription procedure [16]. The qualitative difference between the isochronal thermal curves for H_2-loaded and H_2-free germanosilicate fibers was repeatedly mentioned in literature, both for low-intensity single-quantum [17] and high-intensity two-photon [10] UV irradiations. In this work, we demonstrate that while the FBG inscription at high-intensity 264 nm irradiation in H_2-free standard telecom fiber is accompanied by stress induction, in a hydrogenated SMF-28 no stress is generated during FBG recording up to similar grating strength.

2. Experiment

In the experiments we used the standard telecom SMF-28 fiber (supplied by Elliot Scientific), with a core diameter of 8.2 μm, a cladding diameter of 125 μm and a numerical aperture of 0.14. The fiber was sensitized in a hydrogen atmosphere, typically at 150 bar at 75 °C for 2 weeks. For the inscription of the FBGs we used 264 nm femtosecond pulses generated by a commercially available Nd:glass laser system [13]. The pulse duration was 220 fs (FWHM), the beam diameter was 0.3 cm (FWHM), the repetition rate was 27 Hz and the pulse energy was up to 300 μJ. The laser pulses were focused by a fused silica cylindrical lens, with a 21.8 cm focal distance, through a 1 mm thick phase mask with a 1.07 μm pitch onto the fiber (with acrylate coating removed), resulting in a vertical beam size at the entrance surface of the fiber approximately equal to the diameter of the stripped fiber (for the used range of incident pulse intensities). The fiber was placed behind the phase mask at a distance of about 100 μm. The polarization of the 264 nm femtosecond laser beam was perpendicular to the fiber axis. The length of each FBG was 0.3 cm (FWHM). The experimental techniques used for femtosecond pulse characterization, incident energy acquisition and monitoring of Bragg grating transmission during the inscription were described earlier [9].

The setup used for stress profile measurements was similar to the one reported earlier by Park et al. [18]. The grating was first localized with respect to the end of the fiber by an optical low coherence reflectometry (OLCR) method [19]. The tomographic measurements were executed using an angular spacing of 30 degrees for distributions of cylindrical symmetry. For non-symmetric distributions an angular spacing of 7.5 degrees was used to obtain a better resolution. Using the 10x objective we get a spatial resolution of 0.7 μm. The total axial stress distribution, $\sigma_{zz}^{tot}(r)$, is obtained from an Abel [5] or an inverse Radon transformation [7] of the integrated birefringence (retardation), for fibers with or without cylindrical symmetry, respectively. The retardation values are averaged over a range of 400 μm along the fiber axis. Recent advances in stress measurements of optical fibers have shown that the birefringence measured with the polariscope has a contribution that scales linearly with fiber drawing tension [20, 21]. It is in fact a superposition of elastic stress and inelastic strain [21], which was frozen into the fiber during fiber drawing [22, 23]. Both contributions can be separated if we assume that the area integral of the inelastic strain is constant over the fiber surface. As the area integral over the elastic stress is zero since no external forces are applied, the elastic stress distribution is given by the total axial stress distribution, $\sigma_{zz}^{tot}(r)$, minus its normalized integral over the fiber surface:

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$$\sigma_{zz}^{el}(r)=\sigma_{zz}^{tot}(r)-\frac{1}{A}\int_A \sigma_{zz}^{tot}\,dA \tag{1}$$

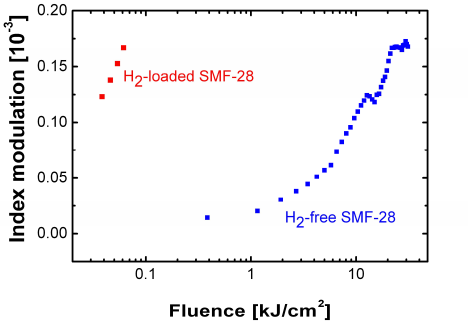

Fig. 1. Refractive index modulation versus fluence dependencies for FBGs inscribed in H_2-free SMF-28 fiber (blue circles) and H_2-loaded SMF-28 fiber (red squares) by high-intensity 264 nm femtosecond pulses. Note that the horizontal axis is in log 10 scale.

3. Results

Figure 1 displays the refractive index modulation growth versus the fluence dependencies for two gratings inscribed by 264 nm femtosecond pulses in SMF-28 fiber, one in a hydrogen-free fiber (with an irradiation intensity of about 300 GW/cm^2) and the other in a hydrogen-loaded one (with an irradiation intensity of about 340 GW/cm^2). It follows, that in order to reach a similar grating transmission of -2.4 to -2.5 dB, one should apply 520 times more fluence to the H_2-free SMF-28 fiber than to the hydrogenated one. To calculate the amplitude and the mean index changes we used a value of 0.75 for the overlap integral. The other FBG parameters are gathered in Table 1. It should be emphasized that at our experimental conditions neither self-focusing nor type II damage took place [24].

Table 1. Laser irradiation parameters and characteristics of the two FBGs.

Sample	Incident intensity [GW/cm^2]	Total fluence [kJ/cm^2]	Grating transmission [dB]	Index modulation [10^{-4}]	Mean index change [10^{-4}]	Core stress changes [MPa]
H_2-free SMF-28	302	31.13	-2.47	1.73	2.49	37.4
H_2-loaded SMF-28	335	0.06	-2.44	1.72	1.75	0

Figures 2(a), 2(b) present the 2D axial stress distribution across the non-hydrogenated SMF-28 fiber before and after the high-intensity femtosecond 264 nm irradiation. In the non-irradiated sample [Fig. 2(a)], the stress has a cylindrical symmetry. The stress is relatively low (−6.5 MPa for the core and the inner cladding) and the fiber has a stress integral of 3.9 ± 0.2 MPa. This value does not change for the irradiated fiber within the accuracy of our measurement, indicating that the local fiber temperature was always below the melting temperature during irradiation. The irradiated sample [Fig. 2(b)] exhibits strong asymmetric stress changes. Figure 2(c) shows the horizontal cuts of Figs. 2(a), 2(b), along the horizontal axis displaying the stress profiles before (blue) and after (red) the femtosecond irradiation. A strong stress increase in the core and also in the cladding after the FBG inscription is obvious. The fiber core has a much higher absorption at the irradiation wavelength due to the GeO_2 concentration than the silica cladding and therefore shows positive stress changes. For a mean index change of $<\Delta n> = 2.49 \times 10^{-4}$ we obtain a core stress change of 37.4 MPa, which gives $\Delta\sigma / <\Delta n>$ of 1.5×10^2 GPa. This stress change per mean index change is in agreement with the value reported recently for an SMF-28 fiber irradiated using 800 nm femtosecond laser

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radiation (1.5×10^2 GPa) [7] and is slightly higher than that for nanosecond UV irradiation (1.3×10^2 GPa) [5, 6].

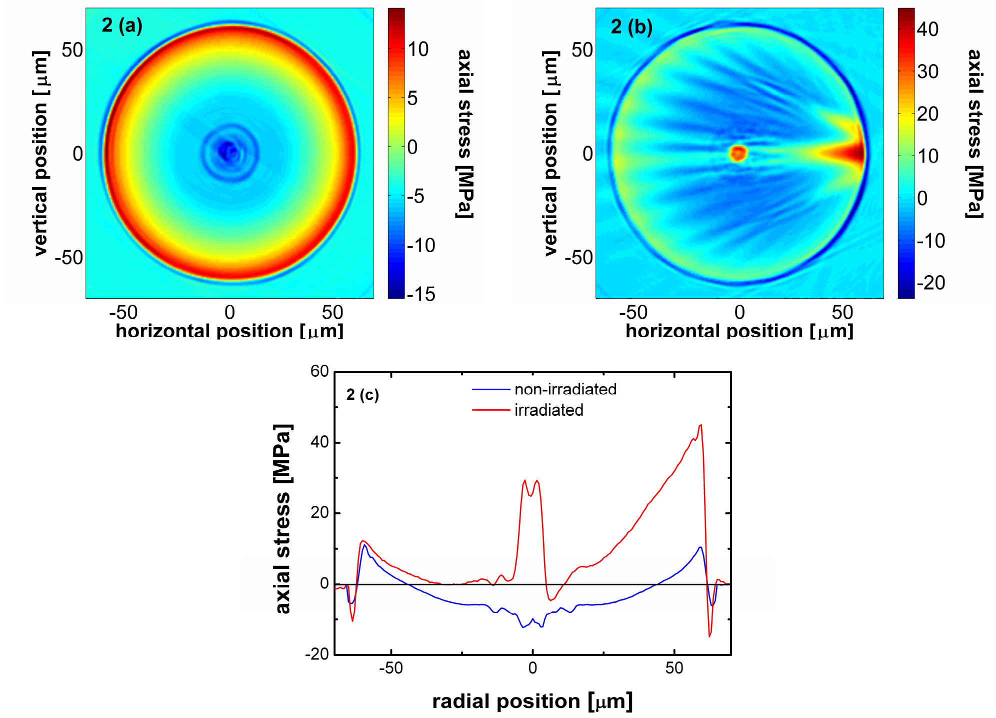

Fig. 2. The 2D tomography pictures of (a) non-irradiated and (b) irradiated (264 nm, 302 GW/cm^2, 31.13 kJ/cm^2) H_2-free SMF-28 fiber; (c) the horizontal stress profiles for non-irradiated (blue) and irradiated (red) H_2-free SMF-28 fiber (cut along the horizontal direction). The light enters the fiber from the left side.

These results show clearly that for non-hydrogenated fibers the dominant mechanism that leads to the core stress changes is compaction of the glass network. The strong stress changes of 35 MPa in the cladding just below the surface are due to a combination of several effects: as we have p-polarized laser light most of the light is transmitted at the air-fiber surface; the laser beam which has an almost constant intensity over the entrance surface is focused by the fiber entrance surface to a spot behind the fiber, thus increasing the intensity at the fiber exit. The high laser intensity leads to two-photon absorption followed by a compaction of the silica network in this area. As a result high positive local stress changes were produced even in pure silica.

Figure 3(a) shows the axial stress distribution in the hydrogenated SMF-28 fiber before the irradiation. After loading a reduction of axial core stress is observed in the core while a stress increase occurs in the fiber cladding to compensate for the H_2-induced changes. The comparison between the non-loaded and loaded fiber is shown in Fig. 3(b). The stress changes in this fiber are quite pronounced over the core and the inner cladding region. This phenomenon is related to the reactions between hydrogen and drawing-induced defects in the fiber core as we reported earlier [25]. In addition the stress integral changed from 3.9 to 5.1 ± 0.2 MPa after H_2-loading. No significant stress change (both in the core and in the cladding) was found in the hydrogenated SMF-28 fiber after 264 nm irradiation [similar to Fig. 3(a)]. Figure 3(c) shows two stress profiles taken in irradiated H_2-loaded telecom SMF-28 at two different positions: in the pristine fiber (blue) and in the grating (red). These results demonstrate that index changes in FBG recorded in H_2-loaded fiber using UV femtosecond irradiation are due to color centers solely and not to the compaction in contrast to the non-hydrogenated fiber. It should be emphasized that the observed effect is specific for the FBGs inscribed in H_2-loaded fibers at high-intensity 264 nm femtosecond UV irradiation. In a separate experiment, 3-mm long FBGs were inscribed in hydrogenated SMF-28 by CW 244 nm light. A total dose of about 0.8–1.0 kJ/cm^2 resulted in a transmission of -15 to -21 dB. *Negative* stress changes (dilatation) of up to -10 MPa were observed (data not shown).

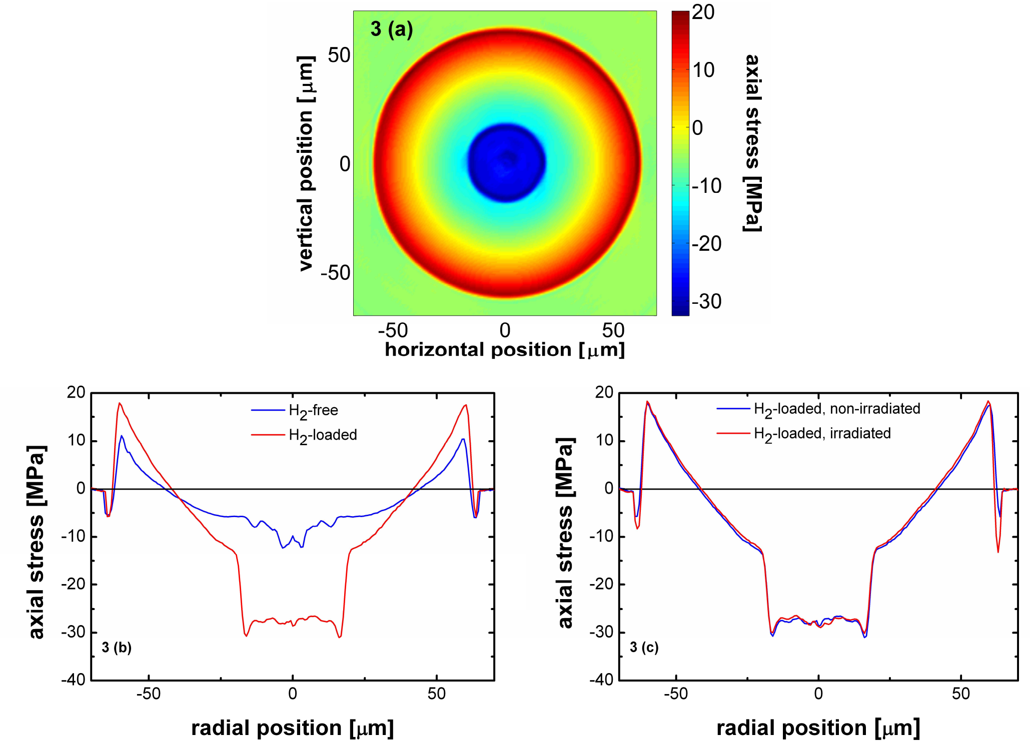

Fig. 3. (a). The 2D tomography picture of the H_2-loaded SMF-28 fiber; (b) the horizontal stress profiles for the H_2-free (blue) and hydrogenated (red) pristine SMF-28 fibers; (c) the horizontal stress profiles for the non-irradiated (blue) and irradiated (264 nm, 335 GW/cm^2, 0.06 kJ/cm^2) (red) H_2-loaded SMF-28 fiber.

4. Conclusion

In summary, the FBGs recorded in H_2-free and H_2-loaded SMF-28 fibers by the two-photon high-intensity UV femtosecond approach reveal two different inscription mechanisms: while in non-hydrogenated telecom fiber, compaction, stress and color centers participate in the creation of refractive index changes; in hydrogenated SMF-28, no compaction was found for femtosecond 264 nm irradiation, leaving only the color-center model responsible for these refractive index changes. The irradiation does not change the inelastic strains, in contrast to H_2-loading.

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