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Tomographic measurement of femtosecond-laser induced stress changes in optical fibers

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The tomographic measurement of the residual stress profile in femtosecond-laser irradiated standard SMF-28 germanium-doped telecommunication fiber is demonstrated. The fiber is irradiated with weakly focused pulses to realize long-period fiber gratings. In the irradiated grating regions, an asymmetrical increase in axial core stress up to 6.2 kg/mm^2 is found. The increase in stress is attributed to a densification of the irradiated glass matrix. The stress-induced anisotropic index distribution is calculated and related to the absolute index change in the irradiated regions. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1762990]

Interaction of ultrashort laser pulses with transparent optical solid matter has been studied extensively in the last 30 years.[1,2] The refractive index modification of the irradiated glass depends strongly on material, focusing, as well as laser parameters. Laser and focusing parameters determine the pulse intensity and power, which can be related to the threshold intensity for optical breakdown and the critical power for self-focusing of the material. If the intensity of the pulse exceeds the threshold intensity, strong plasma formation is observed, leading to a permanent damage of the glass volume. Exceeding the critical power results in self-focusing and laser-pulse filamentation.[3]

Recently, femtosecond laser pulses have been used to write three-dimensional waveguide structures in a variety of bulk glass samples.[4,5] Furthermore, long period gratings[6] as well as fiber Bragg gratings[7] have been realized by modification of the core index in germanosilicate fibers. For waveguide as well as grating formation, intensity and power of the femtosecond pulses are in general below their corresponding threshold values for optical breakdown and self-focusing. Thus, no losses are introduced and the waveguide shape can more accurately be controlled.

The underlying mechanism of the refractive index change in the sub-breakdown intensity region has not yet been completely identified. Raman data indicate an increase in the number of four- and three-membered ring structures for fused silica, which is associated with a densification of the glass after exposure to the femtosecond irradiation.[8] For germanosilicate fibers, it has already been pointed out earlier[9] that UV irradiation changes the Raman spectra of the fiber, indicating a densification of the doped core region. In the case of germanosilicate fibers, the densification is accompanied by a modification of the fiber residual stress profile.[10] An altered stress profile should thus also be found in optical fibers after interaction with femtosecond laser pulses.

We report on direct quantitative measurement of femtosecond laser induced stress modification in the core of germanosilicate fiber. As specimen, long period gratings have been employed, as they provide irradiated as well as nonirradiated sections, and their spectrum further allows one to estimate the induced refractive index change.

Long period gratings have been written in standard SMF-28 telecommunication fiber. Laser pulses of 160 fs duration and 0.27 μJ energy were generated from a $Ti^{3+}:Al_2O_3$ regenerative amplifier (Coherent RegA9000) at a wavelength of 800 nm and a 200 kHz repetition rate. The fiber was translated perpendicularly to the laser beam at a speed of 2.67 μm/s. The laser beam was interrupted periodically with an electronic shutter, resulting in a grating of 40.05 mm length with 450 μm period and duty cycle of 0.5. The pulses were weakly focused onto the fiber core with a 5× microscope objective (NA=0.1). A polarizer ensured a beam polarization perpendicular to the fiber axis. Maximization of the guided fluorescence light in the fiber using a photomultiplier optimized the alignment of the fiber core with respect to the focus of the radiation.

To measure the two-dimensional stress profile, a setup similar to the one presented in Ref. 11 has been installed. The axial stress induced phase retardation profile of the fiber is determined polarimetrically for 60 projection angles from 0° to 180°. The axial stress profile is then calculated by inverse Radon transformation[11] of the projection data. The knowledge of the axial stress distribution σ_{zz} allows calculation of the other components $(\sigma_{rr},\sigma_{\theta\theta},\sigma_{r\theta})$ of the stress tensor.[12] Further, photoelasticity relates the stress tensor to the refractive index tensor,[11] so the stress-induced component of the total refractive index change can be evaluated from stress measurements.

Figure 1 shows the two-dimensional axial stress profile

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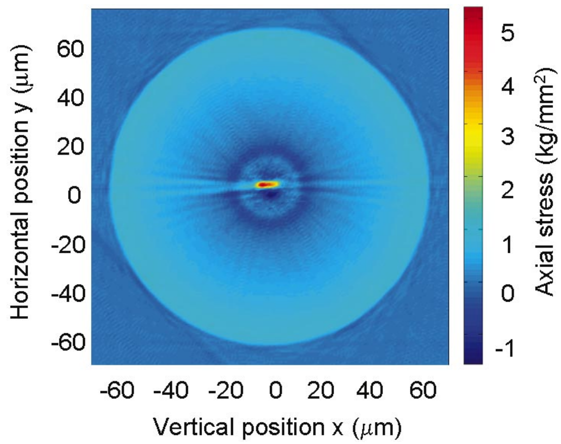

FIG. 1. (Color) Two-dimensional axial stress profile of SMF-28 fiber after irradiation with femtosecond pulses. The fiber was irradiated along the x axis. The peak laser-induced stress is 5.2 kg/mm^2 in the core region.

of the fiber after irradiation with the femtosecond laser pulse train. The x axis is the axis parallel to the incident laser beam. The stress is increased over an almost elliptical region in the core to a peak value of 5.2 kg/mm^2. The core region has a diameter of 8.2 μm and can be identified in Figs. 1 and 2 by its negative axial stress. In Fig. 2, the two cross sections parallel (a) and perpendicular (b) to the incident beam are illustrated and compared to the stress profile in the nonirradiated region. The maximum stress change in the core is found to be about 6.2 kg/mm^2. A small misalignment of the stress-modified region with respect to the core center can be observed in Fig. 2(b). The stress is increased over a length of 8.5 μm [full width at half maximum (FWHM)] and a width of 2.5 μm.

The pulse peak power is estimated to be $P_{\max}=0.94\,E_p/\tau_p=1.59$ MW, where τ_p is the pulse-width (FWHM) of a Gaussian-shaped pulse of energy E_p. The peak power is about four times smaller than the critical power for self-focusing in silica.[2] Above the critical power, catastrophic collapse of the laser beam to a singularity is predicted.[1] Supercontinuum generation and collapse due to self-focusing have been reported to occur above the same power threshold.[13] During the writing process, no supercontinuum generation could be observed by eye in the irradiated regions. We thus conclude that self-focusing is still weak in our case and model the incoming laser intensity to be Gaussian,

$$I(x,y,z)=\frac{P_{\max}}{4w_y(x)w_z(x-x_0)}\times\exp\left[-2\left(\frac{y^2}{w_y^2(x)}+\frac{z^2}{w_z^2(x-x_0)}\right)\right], \quad (1)$$

where the transverse beam dimensions along the laser beam are given by $w_i(x')=w_{0i}[1+(x'/x_{Ri})^2]^{0.5}$, $i=y,z$, with beam waists w_{0i} and Rayleigh ranges $x_{Ri}=\pi\,(w_{0i}^2/\lambda)$ perpendicular ($i=y$) and parallel ($i=z$) to the fiber axis. The offset distance x_0 between the two beam waists reflects the astigmatism introduced by the curvature of the fiber in the y direction. For our focusing conditions, we find $w_{0y}=2.5\,\mu$m, $w_{0z}=1.8\,\mu$m, and $x_0=28.1\,\mu$m. Due to the astigmatism, the two foci do not coincide. The maximum intensity of the beam occurs between them and is found with Eq. (1) to be $I_{\max}=6\times10^{12}$ W/cm^2.

To compare the laser intensity profile with the stress changes shown in Fig. 2, FWHM values of the intensity were calculated in the x and y direction. In the x direction, we get a length of 47 μm, in the y direction a width of 4.2 μm. As mentioned earlier, the FWHM values for the stress change have been found to be 8.5 and 2.5 μm, respectively. If the change in residual stress only depends on intensity, the modified region should thus be more than twice as long. The length of the stress-modified region is rather limited to the extension of the fiber core. We thus conclude that the modification in core stress is strongly supported by the Ge-doping of the core region.

Due to the good quality of the measured grating spectrum,[14] comparison with simulated spectra could be used to estimate the induced index change. Experimental results and synthetic data from grating modeling match well for an induced refractive index change of 4×10^{-4}. The modeling is based on a refractive index that is increased over an azimuthal angle of $0<\phi<120°$ within the irradiated region of the fiber core. The area of index change within the model thus agrees well with the area of stress change measured tomographically (Fig. 1).

For germanosilicate fibers, a linear dependence of refractive index change on axial stress change, $\Delta n=(0.8\pm0.2)\times10^{-4}\,\Delta\sigma_z$, has been reported after irradiation with pulsed UV light.[10] For a measured peak axial core stress increase of 6.2 kg/mm^2, this corresponds to an index increase of $(4.96\pm1.24)\times10^{-4}$. As mentioned earlier, a refractive index change of 4×10^{-4} had been found by modeling the spectra. The two values thus agree well within error, which might indicate that the nature of the glass change introduced by UV and femtosecond laser irradiation is similar in our case, where low energy pulses were weakly focused into the fiber.

To obtain the two transverse components of the photoelastic index change,[11] the stress tensor has been determined

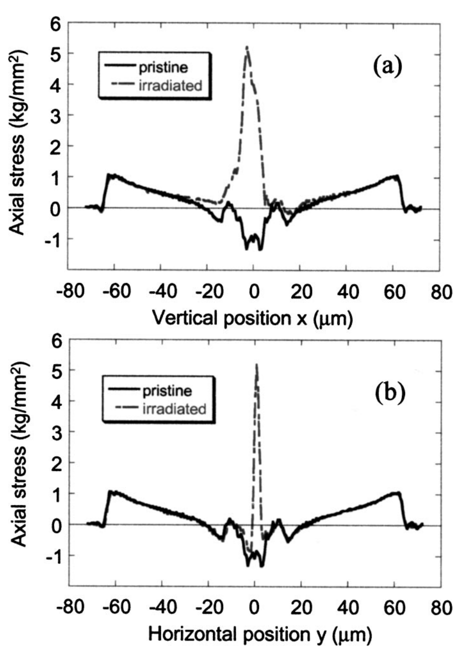

FIG. 2. Axial stress profiles parallel (a) and perpendicular (b) to the incident femtosecond laser pulse train. In the focus region, the peak stress increase is 6.2 kg/mm^2.

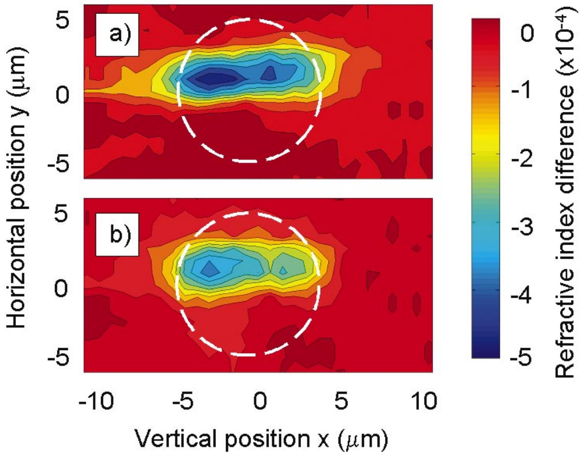

FIG. 3. (Color) Stress-induced change for the x (a) and y (b) component of the refractive index change tensor. The circle indicates the Ge-doped core region.

completely.[12] This allows separating the photoelastic contribution from the total refractive index change.[15] Figure 3(a) shows the stress-induced index change for the x component, Fig. 3(b) for the y component of the refractive index change tensor. For both components, the index change is negative due to the overall tension increase, and peaks at -3.7 and -4.7×10^{-4}, respectively. The modulus of photoelastic index change is thus, as for UV-illuminated germanoslicate fibers,[15] of the same order of magnitude as the total index increase. The inelastic contribution of the total index change must have a magnitude twice as large as the net index change.

For both components, the photoelastic index change in the middle of the modified region is less pronounced than in the adjacent regions. A possible explanation is the lower Ge concentration in the center core region due to the preform fabrication process.

The similarities between the changes in glass properties reported here and for UV irradiation suggest that the underlying mechanisms may be similar. The UV-induced index change in germanosilicate fibers is triggered by photobleaching of Ge oxygen-deficient centers through two-photon absorption.[16] The emerging electron is re-trapped at the original site or at some other defect site. As a result, the shape of the molecule is reconfigured, changing the absorption as well as the density of the material. For irradiation with 240 nm pulses, index changes up to 1.2×10^{-3} have been reported in standard telecommunication fiber.[17]

We suggest that for the femtosecond induced index changes reported here, photoionization is also the triggering mechanism. For 800 nm light, five photons are necessary to bridge the 7.2 eV band gap of Ge-doped silica.[16] Once the corresponding electrons have been shifted to the conduction band, the recombination mechanisms might be similar to the case of UV photo-ionized glasses.

In summary, we have directly measured core stress changes in Ge-doped fibers irradiated with weakly focused femtosecond laser pulses. The peak change in refractive core index was estimated to be 4×10^{-4}. The stress was found to increase by up to 6.2 kg/mm^2 in the focus. Similarities to stress and index changes observed in UV-irradiated fibers suggest that in both cases, the underlying mechanisms in the Ge-doped region are similar. The main difference is the number of photons needed to trigger the mechanisms by electron excitation.

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