Contribution of photoinduced densification to refractive-index modulation in Bragg gratings written in Ge-doped silica fibers

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We have computed the contribution of UV-light-induced densification to the refractive-index modulation of fiber Bragg gratings. Our results confirm that, for strong gratings written in Ge-doped silica fibers with 248-nm UV light, density changes account for a major part of the photosensitivity effect. © 2000 Optical Society of America

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The photosensitivity phenomenon,[1] which is a basis for the fabrication of fiber gratings, is commonly ascribed to two essential physical mechanisms: creation of color centers[2] and structural transformations.[3] Both effects are well established. However, there is no general agreement about which mechanism dominates in the case of type I gratings in Ge-doped silica fibers. The analysis of the color-center contribution assumes a rather straightforward application of the Kramers–Krönig relations.[4,5] The challenge is to measure changes of the extinction coefficient in the deep-UV region, which was demonstrated[5] to account for the major part of the refractive-index perturbation. On the other hand, estimation of the contribution of structural changes requires an analysis of the elasticity problem and computation of the stress distribution induced by a grating inscription. Complicated measurements of the induced birefringence must be followed by a nontrivial analysis of those data. A significant improvement of the understanding of the stress effect was gained recently by use of finite-element analysis.[6]

UV-induced densification of Ge-doped silica is a proven experimental fact.[7,8] The effect can be observed, for example, as a surface corrugation of a thin glass plate that results from a grating inscription. In three-dimensional images obtained with scanning-light interferometry a grating appeared to be embedded in a valley. This was interpreted as a consequence of a density increase. Computations based on a simplified model showed that the contribution of density changes accounts for a large part of the measured refractive-index change.

An interferometric technique was used recently to observe surface corrugations in $14GeO_2 \cdot 86SiO_2$ several-millimeter-thick glass plates under 193- and 248-nm excimer-laser irradiation.[9] The results were interpreted with the aid of a finite-element model, which was stated to be critical for the approach reported there. For the exposure levels that are typically used to write fiber gratings, the densification contribution to the refractive-index change was found to be negligible for 248-nm light. This conclusion contradicts results published by other groups.[7,8,10–12] Although possible explanations were presented by those authors, the reason for the discrepancy remains unclear. The discrepancy shows again the importance of accurate quantification of UV-induced density changes.

We have proposed a phenomenological approach that allows an analytical calculation of the stress distribution in an optical fiber as a result of the inscription of a fiber grating.[13] The elasticity problem was analyzed based on a set of differential equations that describe the effect of density variations.

In this Letter we use the same approach to evaluate the contribution of density modifications to refractive-index modulation in fiber Bragg gratings. First, we derive simple analytical relations that relate the mean value and the amplitude of the refractive-index modulation to the UV-induced density variation. After that we use those relations to analyze experimental data on UV-induced stress measurements. Based on the experimental values, we derive the contribution of the density change to the refractive-index modulation. At the phenomenological level, the effect of density variation on the refractive index is a combination of material-structure transformation (inelastic) and photoelastic effects. A differential form of the Lorentz-Lorenz equation shows that the inelastic contribution is directly proportional to the density change[14]:

$$\Delta n^{\mathrm{in}} = a^{\mathrm{in}}(\Delta\rho/\rho),$$
$$a^{\mathrm{in}} = (1-\chi)(n^2-1)(n^2+2)/6n \approx 0.42, \qquad (1)$$

where $n \approx 1.44$ is the refractive index of the glass at 1.55 μm and the parameter χ accounts for the dependence of refractivity on density. For silica, the experimentally observed evolution of the refractive index as a function of density (under hydrostatic pressure loading) gives a value of χ of 0.2.[15]

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The elastic contribution can be characterized by stress-optical equations. The optical field in a single-mode fiber is described by two LP_{01} modes that have transverse electric fields and polarization vectors that are parallel to an arbitrary pair of orthogonal directions in the fiber cross section. These modes are uniformly polarized. To describe light propagation we use a rectangular system of coordinates with the z axis directed along the fiber axis and LP_{01} modes being x and y polarized. The stress-optical equation for the x-polarized mode is

$$\Delta n_x{}^{\mathrm{el}} = -B_2\sigma_{xx} - B_1(\sigma_{zz} + \sigma_{yy}), \quad (2)$$

where the stress-optical constants B_1 and B_2 for silica at 644 nm are equal to 4.22×10^{-12} and $0.65 \times 10^{-12}\ \mathrm{m^2\,N^{-1}}$, respectively,[16] and σ_{ii}, $ii = xx, yy, zz$ are the components of the stress tensor. A similar equation holds for the y-polarized mode.

Following the standard approach, we assume that only a fiber core of radius R is photosensitive. We also neglect any radial dependence of the density variations inside the core. Under the same assumptions, analytical expressions that describe the distributions of the axial, radial, and hoop stresses were previously derived.[13] The strain tensor ϵ_{ij} can be transformed from a cylindrical to a rectangular system of coordinates in the standard way:

$$\epsilon_{xx} = \epsilon_{rr}\cos^2\varphi + \epsilon_{\varphi\varphi}\sin^2\varphi,$$
$$\epsilon_{yy} = \epsilon_{rr}\sin^2\varphi + \epsilon_{\varphi\varphi}\cos^2\varphi, \quad (3)$$

where φ is the polar angle and the stresses are calculated with the Duhamel–Neumann relations.

We have, for the photoelastic contributions to the mean value of the refractive index,

$$\Delta\bar{n}_x{}^{\mathrm{el}} = -\mu\frac{\mathrm{K}}{\lambda + 2\mu}(3B_1 + B_2)\frac{\Delta\bar{\rho}}{\rho} \approx -\bar{a}^{\mathrm{el}}\frac{\Delta\bar{\rho}}{\rho}, \quad \bar{a}^{\mathrm{el}} \approx -0.19], \quad (4)$$

and for the index-modulation amplitude

$$\Delta\hat{n}_x{}^{\mathrm{el}} \approx -\mu\frac{\mathrm{K}}{\lambda + 2\mu}(B_1 + B_2)\frac{\Delta\hat{\rho}}{\rho} \approx -\hat{a}^{\mathrm{el}}\frac{\Delta\hat{\rho}}{\rho}, \quad \hat{a}^{\mathrm{el}} \approx -0.14]. \quad (5)$$

Here an overbar and a "hat" designate the mean value and the modulation amplitude, respectively; λ and μ are the Lamé coefficients, and $K = \lambda + {}^2\!/_3\mu$. The numerical values in Eq. (4) and relation (5) were computed for silica. For material with $\chi < 1$ and positive stress-optical constants, the inelastic contribution, Eq. (1), and the elastic contribution, Eq. (4) and relation (5), have opposite signs. The reduction of the mean index change is ~45%. For the modulation amplitude the reduction is smaller (33%). This reduction is in agreement with the general principle that a reaction of a stable system reduces the effect of a perturbation.

Measurements of stress distributions related to inscription of fiber Bragg gratings with a refractive-index modulation amplitude of up to 1.2×10^{-3} were published some time ago.[10,12] In those experiments a He–Ne laser beam ($\lambda = 633$ nm) was transversely focused to a small spot on the fiber. The components with polarization parallel and orthogonal to the fiber axis experience different retardation, owing to stress-induced birefringence. We measured this difference by scanning the beam across the fiber, and a radial distribution of the axial stress was computed from the Abel integral equation. The diameter of the probe beam was ~3 μm, and the grating pitch was 0.4 μm. Therefore the results reported here give values of the axial stress averaged over the grating period. Direct comparison of the experimental data and our computations (Fig. 1) is not reasonable because the core diameter of the fibers used in the experiments was the same as the probe-beam diameter, making the experimental data averaged in the radial direction over the core–cladding interface. Therefore we use the value taken at the core center in our computation. In that case the contribution of the probe beam that passed through the cladding can be neglected.

Inscription of a grating breaks the translation invariance of the fiber, resulting in a violation of the sum rule[17]: $\sigma_{zz}(r, z) \neq \sigma_{rr}(r, z) + \sigma_{\varphi\varphi}(r, z)$. This is not surprising, because the sum rule was established for spatially uniform cylinders. However, it can be seen from Fig. 1, and also proved accurately by use of the results reported by Gusarov *et al.*,[13] that the sum rule is true on average: $\bar{\sigma}_{zz}(r) = \bar{\sigma}_{rr}(r) + \bar{\sigma}_{\varphi\varphi}(r)$. This result explains why one can apply the sum rule to compute the average hoop stress in fiber gratings.

An approximately linear dependence of the refractive-index modulation amplitude on the average axial stress was observed experimentally,[12] with the proportionality coefficient equal to $(0.8 \pm 0.2) \times 10^{-11}\ \mathrm{m^2\,N^{-1}}$. In the linear theory developed in Ref. 13 the average axial stress is proportional to a density change:

$$\bar{\sigma}_{zz} = [\mu K/(\lambda + 2\mu)]\Delta\bar{\rho}/\rho. \quad (6)$$

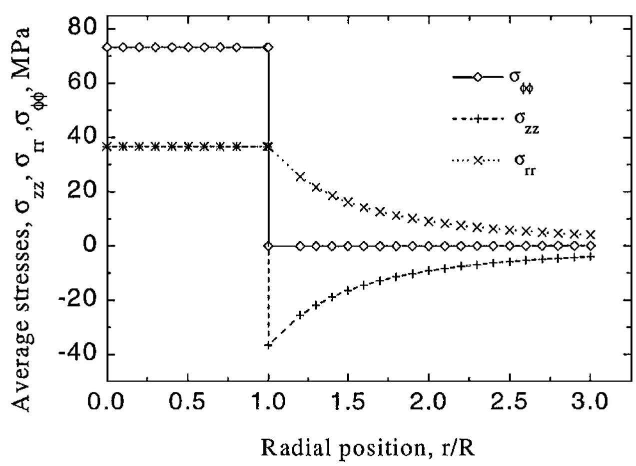

Fig. 1. Radial distributions of axial, radial, and hoop stresses averaged over the fiber grating period. The radius of the photosensitive Ge-doped silica core is 4 μm. The density variation in the axial direction is assumed to be sinusoidal, with an average value of $\Delta\bar{\rho}/\rho = 0.5\%$.

Equation (6) is a form of Hook's law. A dilatation center with an additional volume ΔV_d gives rise to a sample-volume change $\Delta V = [3K/(\lambda + 2\mu)]\Delta V_d$. Taking into account that $\Delta V/V \approx 3\Delta L/L$, where L is the sample length, we can rewrite Eq. (6) as

$$\bar{\sigma}_{zz} = -\mu(\Delta L/L). \tag{7}$$

For nearly ideal gratings $\hat{\sigma}_{zz}(r) \approx \bar{\sigma}_{zz}(r)$, and we have, from Eqs. (1) and (4), and relation (5),

$$\begin{aligned}\Delta\hat{n}_x{}^{\mathrm{el}} &\approx a^{\mathrm{in}}\Delta\hat{\rho}/\rho - (B_1 + B_2)\hat{\sigma}_{zz} \\ &\approx 0.96 \times 10^{-11}\ \mathrm{m}^2\ \mathrm{N}^{-1}\bar{\sigma}_{zz},\end{aligned} \tag{8}$$

in good agreement with the experimental value. The computed value is slightly bigger than the experimental one. The difference could be a result of the saturation effect. This saturation is rather weak owing to the high fringe visibility achieved in the experiment.[12]

We can also compute the contribution of the density modification to the refractive-index change. The reported induced axial stress of 124 MPa at a fluence of 33 $\mathrm{kJ/cm^2}$ corresponds to a mean densification of 0.82% [Eq. (6)]. Equation (4) and relation (8) give 1.18×10^{-3} for the index-modulation amplitude and 0.99×10^{-3} for the mean value, whereas the experimental values are 1.15×10^{-3} and 0.96×10^{-3}, respectively. This result shows that for nearly perfect strong gratings written in Ge-doped silica, density changes can account for a major part of the photosensitivity effect, whereas the contribution of the color centers is within the measurement uncertainty.

Results of high-resolution stress-distribution measurements in UV-irradiated fibers were reported recently.[11] Irradiations were performed at 193 and 248 nm. In both cases an increase of the axial tensile stress was observed for Ge–Bo-codoped fiber. Inscription of a grating with 193-nm light resulted in an axial stress-modulation amplitude of 20 MPa for a fluence of 0.4 $\mathrm{kJ/cm^2}$. According to Eq. (6), such stress modulation corresponds to a refractive-index modulation of 1.92×10^{-4}. The refractive-index modulation amplitude computed from the grating reflectivity is ~40% higher: 2.7×10^{-4}. However, the averaging length of 0.3 μm, which corresponds to the experimental resolution, is only 3.3 times shorter than the grating pitch. Such averaging results in underestimation of the modulation amplitude by a factor of $\sin(0.15\pi)/(0.3\pi) \approx 0.86$. Accounting for this factor increases the contribution to 80%. The remaining 20% difference can be attributed to the color-center contribution. This result is in agreement with a hypothesis that color centers are of importance for the initial stage of grating inscription, whereas density changes dominate the photosensitivity effect for increasing levels of accumulated UV fluence.

In conclusion, we have derived simple analytical expressions that quantify the effect of UV-light-induced density changes on the refractive index of glass in optical fibers. The results of our computations are in good agreement with published experimental data. They provide additional support for a model that invokes structural changes as a major contribution to UV-induced refractive-index changes. We have found that, for gratings written in Ge-doped silica fibers with large refractive-index modulation amplitudes, the photosensitivity is dominated by the contribution of the density effect.

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