Bragg gratings in defect-free germanium-doped optical fibers

J. Albert, K. O. Hill, D. C. Johnson, F. Bilodeau, and S. J. Mihailov

Communications Research Centre Canada, P.O. Box 11490, Station H, Ottawa, Ontario K2H 8S2, Canada

N. F. Borrelli and J. Amin

S&T Division, Corning, Inc., Corning, New York

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Bragg gratings have been written in germanium-doped optical fibers that have been treated to remove the UV absorption bands associated with oxygen-deficient defects. When one is using high-intensity 193-nm light from an ArF excimer laser to fabricate the gratings, the refractive index increases and the grating transmission spectra are similar to those obtained in standard (untreated) fiber. © 1999 Optical Society of America

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The photosensitivity of germanium-doped silica optical fibers[1] is traditionally associated with the presence of so-called germanium oxygen–deficient centers (GODC's), because of the strong absorption band of these defects near 244 nm.[2,3] On the other hand, it has been demonstrated that higher photosensitivity ($\Delta n > 10^{-3}$ instead of $\Delta n = 10^{-4}$) can be achieved by irradiation of fibers with relatively low germanium content by use of high-intensity 193-nm excimer-laser light rather than light with a wavelength near 244 nm.[4] In this case the proposed explanation for the large photosensitivity is based on two-photon absorption, which leads to glass-network bond breaking and concomitant structural relaxation and in turn to local compaction.[5,6] In an attempt to increase our understanding of these seemingly contradictory results, here we present experiments on the photosensitive behavior of optical fibers that we have specially treated to remove the 244-nm UV optical absorption band associated with GODC's.

In these experiments we use a fiber based on the standard Corning SMF 1528 fiber-preparation method. This is an outside-vapor-deposition technique in which a silica germania soot blank is obtained through flame hydrolysis of silicon and germanium precursors. The soot blank at this stage is porous and is subsequently consolidated at 1400–1500 °C in a dry helium ambient atmosphere. In the normal process the oxygen's partial pressure is less than 1 part in 10^6. This low partial pressure leads to a blank with a distinctive absorption feature at 244 nm (Fig. 1). The so-called defect-free fiber is prepared from a soot preform that is consolidated in an atmosphere of 50% oxygen; the balance of the atmosphere is helium. In this case no absorption features are discernible near 244 nm (Fig. 1). Both spectra are measured on 0.5-mm-thick preform slices by use of a Cary 3E spectrophotometer.

As far as quantifying the photosensitivity of fibers drawn from these two kinds of preform, is concerned, the method is based on the formation of a Bragg grating by irradiation of the fiber through a phase mask.[7] Broadband light near 1550 nm from a pumped erbium-doped fiber is launched into the fiber, and the transmission is measured in real time during the grating exposure by an optical spectrum analyzer with 0.1-nm resolution. A computer is used to extract the grating reflectivity and the center wavelength from the measured spectrum every few seconds. The laser used for irradiating the fiber through the mask is a Lumonics PM-846 excimer laser operating at 193 nm, with a nominal pulse width of 14 ns and a repetition rate of 100 pulses/s. We determine the pulse-energy density by measuring the pulse energy going through a known aperture near the fiber location and factoring in the magnification factor of the cylindrical

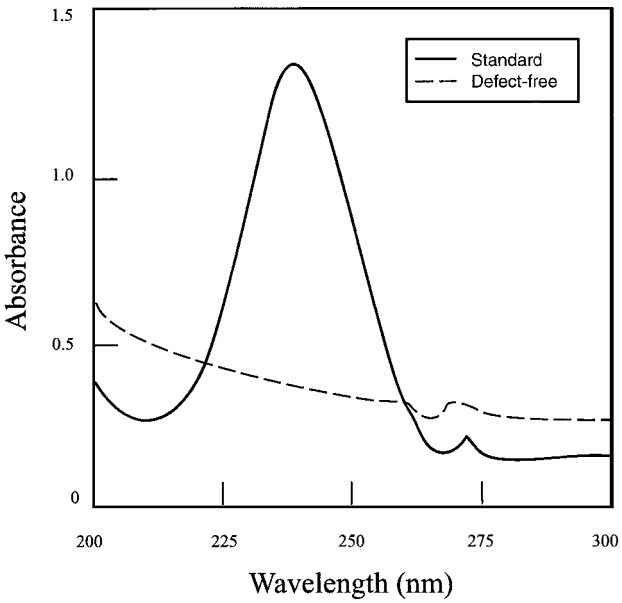

Fig. 1. UV-absorption spectra of the preforms used to fabricate the fibers. The small feature near 270 nm is an instrument artifact. Absorbance is defined as optical density per centimeter. Solid curve, standard consolidation with 1-part-in-10^6 oxygen; dashed curve, preform consolidated in 50% oxygen ambient.

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lens that is used to concentrate the laser light on the fiber–mask assembly. We obtain the two laser pulse-energy densities, 200 and 350 mJ/cm^2, by changing the discharge voltage of the laser but keeping all other parameters fixed. The absolute value of the pulse-energy density obtained in this manner is accurate to $\sim\pm 20\%$.

The experimental data presented below show the total UV-induced refractive-index change in the fibers, which we obtain by summing the average and the modulation-amplitude contributions. This sum is representative of the peak refractive-index increase in the bright fringes of the laser irradiation as long as the pattern of the induced index is reasonably sinusoidal, regardless of the modulation depth of the pattern. The UV-induced refractive-index modulation amplitude is extracted from the grating reflectivity by use of standard coupled-mode equations and assumption of an overlap of 0.8 between the guided mode and the cross section of the index modulation (the core–cladding index difference for these fibers is $\sim$0.003 at 1550 nm). The UV-induced average refractive index is calculated from the shift in the center wavelength of the grating. We limit the grating length to 4 mm to be able to resolve fully the grating reflectivity at 0.1-nm resolution.

The growth curves of the UV-induced refractive-index change are presented in Fig. 2 for the two kinds of fiber and for two different values of the laser pulse-energy density (all other conditions are kept identical). In most cases we present two results to show the reproducibility of the experiments. At the lower laser intensity the growth of the induced index is monotonic and almost linear in both cases, but the rate of growth is higher for the standard fiber. When the laser pulse-energy density is increased, however, a notable difference in behavior occurs. The first remarkable result is that index increases of the order of 10^{-3} are achieved both in the standard fiber and in the treated fiber. The second noticeable feature is that the index growth remains quite linear in the treated fiber but shows a kink in the standard fiber. Although the initial growth rate is higher in the standard fiber (2.3 versus 1.4×10^{-6} s^{-1}), the final growth rate (for irradiation times greater than $\sim$4 min) tapers off for the standard fiber to a linear rate of 1.1×10^{-6} s^{-1}, or 50% less than that of the treated fiber. One explanation for this effect is that linear absorption by GODC's initially plays a role in the standard fiber, accelerating the index growth, but that, once the GODC precursors are exhausted, the two-photon regime takes over. The reason for the smaller two-photon growth rate in the standard fiber might be the same as the one that was invoked in the case of fibers with higher germanium content,[4] i.e., higher residual linear absorption leading to less available intensity for the two-photon process.

The fact that the same large value of Δn is obtained in both types of fiber supports the conclusions presented in Ref. 4 regarding the intrinsic nature of the photosensitivity obtained with high-intensity ArF-laser light. Our assertion is that for high UV intensity and long time scales the induced index relies not on defects or linear absorption but rather on two-photon absorption of network bonds involving at least one germanium atom. No saturation of the growth is observed on the time scale shown, indicating that the precursors (all germanium atoms if our hypothesis is correct) are not exhausted. Whether a color-center or a densification model is the explanation for the index change owing to two-photon absorption has not been resolved, however, given the difficulties in measuring absorption changes in the vacuum UV (wavelengths shorter than 190 nm).

In an attempt to quantify the contribution of laser-induced densification to the index change obtained here, the model of Borrelli and co-workers[8,9] has been used. In Ref. 9 it was shown that the densification rate of germanium-doped silica is composition dependent and further that the densification rate of 193 nm is significantly larger than at 248 nm. Moreover, it was shown that densification of a bulk $22\%GeO_2$–$78\%SiO_2$ glass sample could yield a significant refractive-index change, given sufficient exposure. According to their finite-element calculation, as applied to the fiber grating structure and extrapolated to the irradiation conditions used here, the index change grows linearly as a function of exposure and contributes $\sim$40% of the total values shown in Fig. 2. Therefore, according to the model, densification alone cannot account for the measured index change, although it makes a significant contribution.

The final results pertain to the spectral quality of the gratings obtained in both types of fiber. Figure 3 shows that the spectral response of typical gratings written at the higher laser intensity is similar and

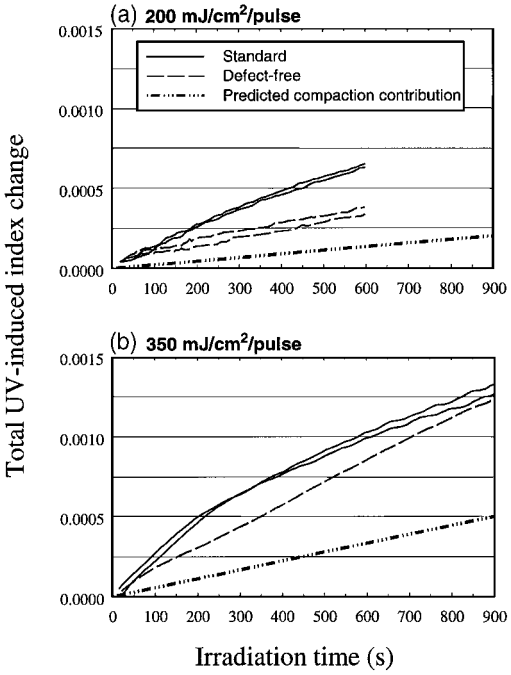

Fig. 2. UV-induced refractive-index changes obtained in fibers irradiated with ArF-laser light. Each curve corresponds to a separate experiment: (a) 200 (mJ/cm^2)/pulse, (b) 350 (mJ/cm^2)/pulse. The dotted–dashed curves represent the contribution of laser-induced densification to the index increase according to the model presented in Ref. 9.

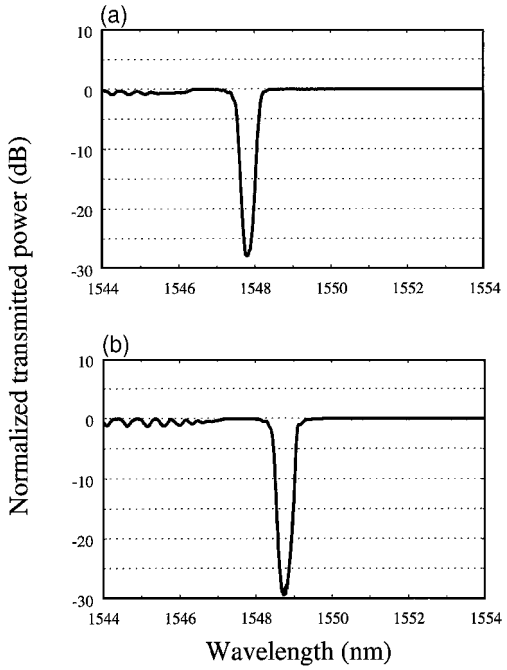

Fig. 3. Transmission spectra of Bragg gratings written in (a) standard and (b) defect-free fibers.

of high quality. The shift in the wavelength of the Bragg resonance is due to a slightly different initial core index in the treated fiber. Apart from the main Bragg resonance, the only noticeable features are the transmission dips on the short-wavelength side of the resonance. These dips are due to coupling to cladding modes, an unavoidable feature of fibers in which the photosensitivity is limited to the core only.[10] The fact that the cladding-mode coupling is similar in both fibers indicates that the uniformity of the UV-induced index change across the core is approximately the same[11] in spite of our speculation that the residual absorption of the defect-free fiber at 193 nm is lower.

In conclusion, it has been demonstrated that in the two-photon regime (high-intensity ArF excimer-laser light) GODC defects are not necessary for UV-induced index changes of the order of 10^{-3}. Although the index-growth dynamics are somewhat different in fibers with and without defects, the final index change and grating spectra can be similar with sufficient exposure.

J. Albert's e-mail address is jacques.albert@crc.ca.

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