Grating formation in pure silica-core fibers

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Strong grating formation in pure silica-core fibers by use of 193-nm ArF-laser radiation is reported. Unsaturated refractive-index changes of $\Delta n \sim 0.3 \times 10^{-3}$ were observed in nontreated fiber, and changes of $\Delta n \sim 0.5 \times 10^{-3}$ were observed in fibers with a high hydroxyl concentration. Possible mechanisms of photosensitivity in pure silica-core fibers are discussed. © 2002 Optical Society of America

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Fiber Bragg gratings have matured as a technology and are now routinely used in several applications in telecommunications and sensing. The photosensitivity of the fiber[1] is of great importance for the final strength and spectral quality of the grating. Although gratings have been recorded in several germanium-free fibers,[2] highly photosensitive fibers are usually doped with germanium. Photosensitivity is often characterized by the absorption band at 242 nm, which is associated with the concentration of germanium–oxygen-deficient centers (GODCs).[3] In Ref. 4, strong grating formation was reported in germanium-doped fiber in which the germanium–oxygen-deficient center had been eliminated by special preform manufacturing. Grating formation in this fiber was attributed to a two-photon- (193-nm-) mediated process, whereas in the presence of germanium–oxygen-deficient centers the process was shown to be one-photon mediated. Previously reported refractive-index changes in pure silica were typically $\Delta n \sim 10^{-5}$ (Ref. 5) and were also associated with a two-photon- (193-nm-) mediated process. For most fiber Bragg grating applications this value is too small to produce useful fiber components.

In this Letter we report on the formation of strong gratings in pure silica-core fibers by use of 193-nm ArF-laser radiation. Gratings were successfully written in fibers that were not treated, in hydrogen- or deuterium-loaded fibers,[6] and in hydrogen-loaded fibers subject to thermal treatment (OH flooding[7]). Possible mechanisms of photosensitivity in pure silica-core fibers are discussed.

The silica fiber used in the experiments was manufactured at Acreo with a pure silica core and fluorine-depressed cladding by use of standard modified chemical-vapor deposition technology. The core diameter was 8.4 μm, with a core-to-cladding refractive-index step of $\Delta n_{\text{core-clad}} \sim 5.5 \times 10^{-3}$. The fiber was drawn at a relatively low temperature, possibly resulting in high strain in the fiber at the core–cladding interface. Hydrogen-loaded fibers were prepared at room temperature for 18 days at 10.5-MPa pressure, and deuterium-loaded fibers were prepared at 50 °C for 5 days at 10-MPa pressure. When OH flooding was used, a section (~22 mm) of hydrogen-loaded fiber was heated at ~1000 °C for 1 s. Gratings with a length of 5 mm were written with the 193-nm UV wavelength from an ArF laser at 100 pulses/s with a 10-ns pulse duration. The energy density was estimated to be 0.2–0.4 J cm^{-2} per pulse. The refractive-index modulation was calculated from grating reflection spectra, and the average change in refractive index was calculated from the change in grating wavelength.

As the experimental setups were changed during the course of this work, two sets of measurements were performed. In the first set a phase mask with zero-order nulling of <5% at 193 nm (a good-contrast UV pattern) was used. A section of hydrogen-loaded fiber was OH flooded and then left at standard room temperature and pressure for 14 days so that the remaining hydrogen in the fiber would be removed. Gratings were written in the OH-flooded region and outside the OH-flooded region (outgassed). In the second set of measurements a phase mask with zero-order nulling of >10% (a poor-contrast UV pattern) was used. Gratings were written in deuterium-loaded and in nonloaded (pristine) fiber. For comparison, gratings were also written in standard telecommunications fiber (Corning SMF28). The deuterium-loaded fiber was left at standard room temperature and pressure for 7.5 days before inscription (partially loaded).

When the pure silica fiber was OH flooded for 1 s at 1000 °C, an increase in absorption of ~0.15 dB/cm was observed at 1.39 μm, corresponding to the first overtone of SiOH. When the heating time exceeded 1 s, a decrease in absorption was observed, as shown in Fig. 1 for a temperature of 900 °C. At 1000 °C the process was similar but more rapid. The decrease in absorption is attributed mainly to diffusion of hydroxyl species and molecular water from the core, which reduces the concentration of hydroxyl species. The dynamics are very similar to those of OH flooding in germanium-doped fibers, shown in the inset in Fig. 1, but with a much higher induced absorption in germanium-doped fibers.[7]

The growth in refractive-index modulation in OH-flooded and outgassed fibers, from the first set of

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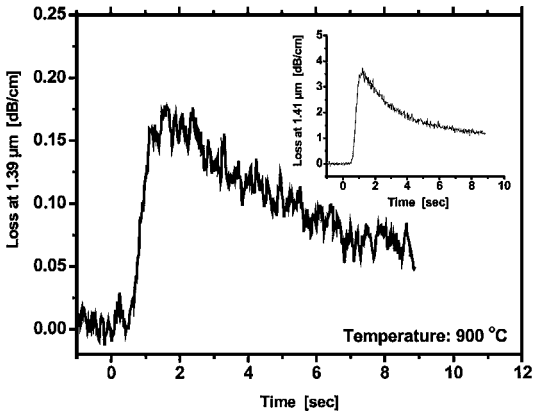

Fig. 1. Dynamics on hydroxyl absorption during OH flooding in pure silica fiber and (inset) germanium-doped fiber.

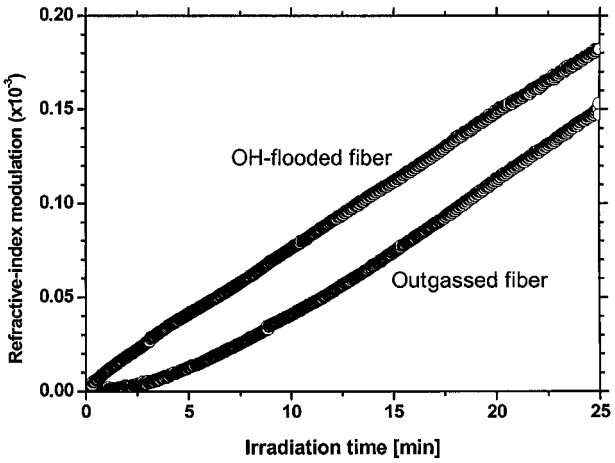

Fig. 2. Growth in refractive-index modulation for OH-flooded and outgassed fibers.

experiments, is shown in Fig. 2. For the OH-flooded fiber the change in refractive index grows linearly in time, whereas for the outgassed fiber there is an initial slow increase in refractive-index modulation with a positive derivative that becomes linear after approximately 10 min of exposure. The growth rate of the refractive-index modulation becomes similar after the initial nonlinearity (~10 min). Neither curve saturates for refractive-index modulations as high as $\Delta n \sim 0.2 \times 10^{-3}$. In the OH-flooded fiber the refractive-index modulation is less than the average refractive-index change (by approximately a factor of 2, yielding a peak index change of $\sim 0.5 \times 10^{-3}$), indicating a loss of contrast, whereas in the outgassed fiber the refractive-index modulation is equal to the average refractive index, yielding a peak index change of $\sim 0.3 \times 10^{-3}$. The spectral quality of the gratings that were written was excellent, as shown in Fig. 3 by the transmission and reflection spectra of the grating written in the outgassed fiber.

In the second set of experiments the grating written in deuterium-loaded pure silica fiber reached an unsaturated refractive-index modulation of 5×10^{-5} in 15 min, whereas the same exposure yielded a refractive-index modulation of 1.3×10^{-5} in the pristine fiber shown in Fig. 4. For comparison, the refractive-index modulation after 3-min exposure of unloaded standard telecommunications fiber (SMF28) was 1.7×10^{-4}.

Experiments were also performed with an excimer-laser-pumped frequency-doubled dye laser at 242 nm, with a fluence of $\sim 10^{-1}$ J/cm^2 per pulse at a repetition rate of 30 Hz. In this case, however, no grating was recorded and no visible luminescence could be observed even in OH-flooded pure silica fiber during exposure.

For efficient writing of gratings in pure silica-core fibers, the UV absorption in the cladding should be lower than in the core, or the grating will be written mainly in the cladding. In our experiments a few factors may have contributed to an increase in the relative absorption of the core. First, it is known that fluorine doping in silica lowers absorption at shorter wavelengths,[8] resulting in lower absorption in the cladding than in the core at the writing wavelength. Second, fiber-drawing parameters change in the concentration of available reactive sites in the core region. In the case of OH flooding, an additional mechanism may be in place. In germanium-doped fiber the amount of OH

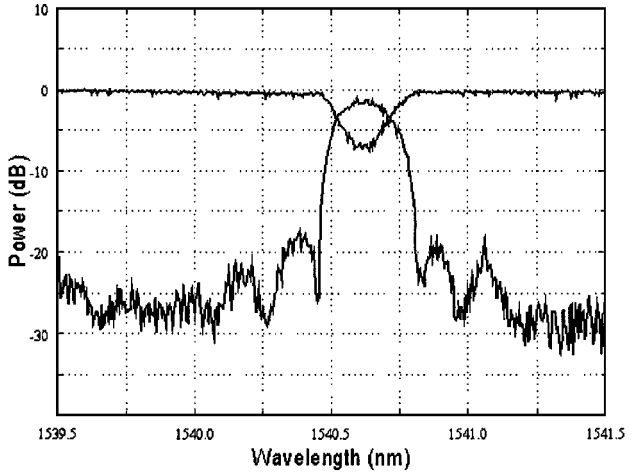

Fig. 3. Transmission and reflection characteristics of a grating written in outgassed fibers.

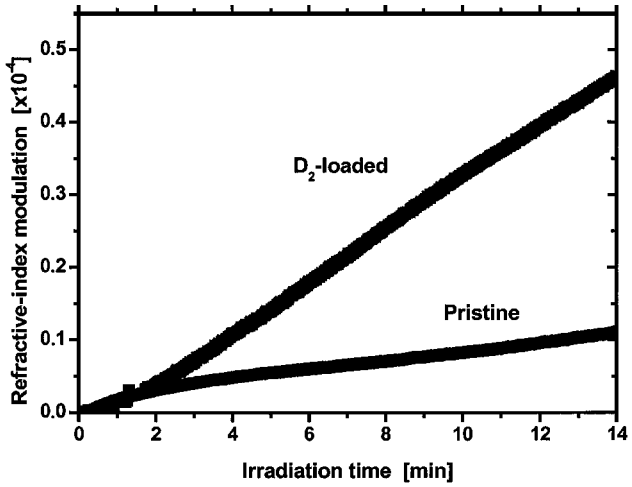

Fig. 4. Growth in refractive-index modulation for deuterium-loaded and pristine fibers.

formation during OH flooding is much greater in the core than in the cladding, probably because of a lower activation energy associated with germanium doping and a consequently larger number of available reactive sites. As the heating continues, the hydroxyl species diffuse, thus reducing the OH absorption in the core. Similar dynamics are seen in the case of pure silica fibers. That this is so indicates that there are fewer available reactive sites in the cladding and possibly that the activation energy for OH formation in the cladding is higher than in the core. The implication of this is that defects created during the 1-s heat treatment of OH flooding are present mainly in the core, favoring absorption of UV in the core as compared with the cladding.

For the outgassed fiber the refractive-index modulation is approximately equal to the average refractive-index change, indicating that a two-photon process occurs in which a nonlinear mechanism enhances the contrast. In the OH-flooded fiber, defects may increase absorption at 193 nm, making one-photon absorption probable. Although this one-photon absorption is an advantage in terms of photosensitivity, an index change is written even where the interference pattern should nominally be dark, leading to the observed loss of contrast. In pristine, outgassed, and loaded fibers, intense ArF light could cause a two-photon-mediated process, resulting in (a) a redshift of the bandgap, (b) weakening of bonds, and (c) wider energy distribution of defects. A shift of the bandgap would make a two-photon process even more likely, as observed in bulk silica exposed to millions of strong ArF pulses,[5] resulting in refractive-index changes of $\Delta n \sim 5 \times 10^{-5}$. A two-photon-mediated process during grating inscription has also been observed in defect-free Ge-doped fibers.[4]

The low temperature during fiber drawing might also be an important factor in determining the magnitude of the observed refractive-index modulation. In this case, relaxation is likely to occur at the core–cladding interface as a result of preexisting stress on the core. Further comparisons between the two sets of experiments are difficult, as conditions were different (especially contrast after the phase mask).

Strong grating formation in pure silica-core fiber has been achieved in untreated, hydrogen-loaded, and OH-flooded fibers. This grating formation allows fabrication of gratings for special telecommunications, sensor, and short-wavelength laser applications (fibers and planar waveguides) and new devices and components fabricated, for instance, in holey and photonic-bandgap fibers.[9]

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