APPLIED PHYSICS LETTERS **89**, 101127 (2006)

Strong Bragg gratings in phosphate glass single mode fiber

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(Received 14 June 2006; accepted 18 July 2006; published online 8 September 2006)

Bragg gratings with reflectivities greater than 99% have been fabricated in phosphate glass single mode fibers by irradiating the fibers with 193 nm wavelength, high intensity pulses from an ArF excimer laser through a phase mask. Thermal treatment for 1000 h at temperatures up to 170 °C did not degrade the gratings and resulted in an increase in grating strength. The refractive index modulation amplitudes obtained exceed 10^{-4}. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2349318]

Commercial fiber lasers almost exclusively use rare earth doped silica based optical fiber as the active material in combination with fiber Bragg gratings (FBGs) that provide the appropriate optical feedback at the emission wavelength. This combination enables all-fiber, monolithic devices with low-loss fusion splices between the different silica fiber components. On the other hand, doped phosphate glasses appear to be the best active material for many bulk lasers.[1] These glasses allow for extremely large doping levels with negligible clustering effects. Er/Yb codoped phosphate glasses exhibit the additional advantage of having a very high phonon energy and, consequently, a high energy-transfer efficiency from absorbing Yb ions to emitting Er ions. The main drawback of this choice for fiber devices is the lack of photosensitivity of phosphate glasses[2,3] that, to the best of our knowledge, has prohibited direct writing of gratings into phosphate glass fibers. Therefore, the application of doped phosphate glasses in active fiber devices has been limited to a few specialty cases that are essentially hybrid glass devices with deposited thin film coating mirrors or FBGs in silica based fiber sections fusion spliced to the phosphate fibers.[4–7] In these devices both optical losses and mechanical instabilities at the splicing points present inherent challenges due to large differences in thermal properties, such as melting temperature and thermal expansion coefficient, between the different glasses.

Here we report on direct writing of strong FBGs in phosphate glass single mode fibers. The FBGs were fabricated by irradiating the fibers with 193 nm wavelength, high intensity pulses from an ArF excimer laser through a phase mask. We demonstrate gratings with more than 99% reflectivity and show that not only the gratings are stable when they are exposed to temperatures up to 170 °C for extended periods (hundreds of hours), but also the reflectivity, in fact, grows under such condition. A small thermal decay occurs when exposing the grating to 400 °C for 1 min and the reflectivity decreases from 99.9% to 99.7%.

The fibers used in the experiments were made of phosphate glasses provided by NP Photonics. The preforms were drawn into single mode fibers with core diameters of 13.5 μm, outer diameters of 125 μm, and a numerical aperture of 0.08. For the grating writing experiments, short lengths (5–10 cm) of the phosphate fibers were spliced to standard telecommunications fiber pigtails (Corning SMF-28) and positioned immediately behind a silica phase mask used to define the grating pattern. The mask had a period of 976.3 nm, corresponding to a fringe pattern period of 488.15 nm in the fiber. The diffraction efficiency of the best available mask was optimized for 248 nm instead of 193 nm, greatly reducing the fringe contrast of the 193 nm exposure because 10% of the zero order light was reaching the fiber without diffraction. We used a GSI Lumonics PM-848 laser equipped with an unstable resonator cavity and filled with an ArF mixture to generate 193 nm light. The laser was generating 80 mJ pulses at 100 Hz, and the pulses had durations of approximately 14 ns. An aperture was used to select the most homogeneous part of the excimer laser beam pattern, which was then expanded and imaged onto the fiber over a length (L) of 14 mm and a fluence per pulse of 400 mJ/cm^2. The reflectivity (R) of the grating was monitored *in situ* during the irradiation by launching broadband light from a pumped Er-doped fiber amplified spontaneous emission source and measuring the reflected or transmitted light spectra with an optical spectrum analyzer (Ando AQ6317B). Following the irradiation, the fiber gratings were placed in a temperature controlled oven and remeasured at regular intervals over 1000 h (the fibers were removed from the oven and allowed to cool to room temperature for each measurement).

Figure 1(a) shows the growth of the grating reflectivity and central wavelength with increasing UV dose. The central wavelength (λ_{Bragg}) shift gives a direct measure of the modal effective index (N_{eff}) of the fiber since $\lambda_{\text{Bragg}}=2N_{\text{eff}}\Lambda$, where Λ is the grating period in the fiber, a fixed parameter determined by the phase mask.[8] A shift in λ_{Bragg} reveals the average change of the refractive index of the fiber induced by the irradiation. The reflectivity is directly related to the refractive index modulation amplitude (Δn) of the gratings through the equation $R=\tanh^2(\pi\Delta nL\eta)$ where η is the overlap factor between the core mode and the cross section of the refractive index modulation[8] [assuming an overlap of 1 yields a lower bound on the refractive index modulation amplitude, this is the approach taken here since we have no information on the relative photosensitivity of the core and cladding. In addition, the transmission spectra shown in Fig. 3(a) below indicate no coupling to cladding modes and hence good overlap[8]]. The results of Fig. 1(b) demonstrate that the aver-

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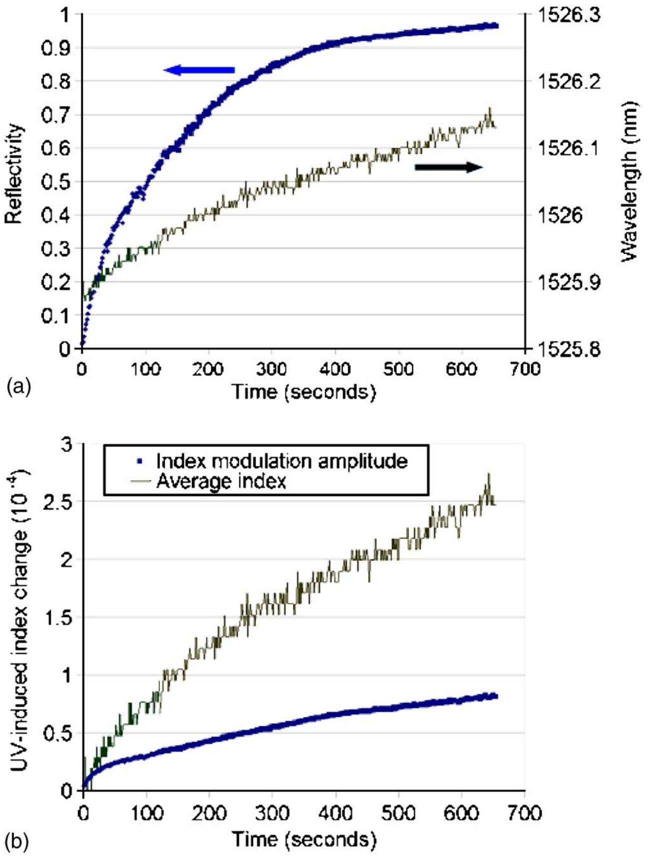

FIG. 1. (Color online) (a) Reflectivity and Bragg wavelength evolution during fabrication of a 14 mm long grating with 10 pulses/s and 200 mJ/cm^2 pulse. (b) UV-induced refractive index modulation amplitude and average value deduced from data of (a).

age index change induced by the irradiation is positive and significantly larger than the index modulation amplitude. In the case of a perfect grating with 100% fringe contrast and strictly positive index change, the modulation amplitude is equal to the average induced index change. We observed smaller modulation amplitudes and attribute the loss of contrast in great part to the phase mask used, which was not optimized for 193 nm operation. However, and most importantly, even under these less than optimal conditions, the results indicate that useful reflection gratings can be formed with this process, without having to sensitize the fibers, e.g., through hydrogen loading, as is required in standard germanium-doped silica fibers.[9]

One of the main concerns with photoinduced refractive index changes is their thermal stability.[10] In order to investigate the thermal reliability of these gratings we put several samples in an oven maintained at 100 °C to monitor their decay. It turns out that the grating reflectivities increased instead of decaying, as shown by the growth in refractive index modulation plotted in Fig. 2 for two gratings with different initial reflectivities. Further increase in temperature to 170 °C led to even larger growth of the refractive index modulations. In the two cases shown, the refractive index modulation amplitude is more than doubled. Finally, we performed a quick annealing at approximately 400 °C with a heat gun for about 1 min and observed a minimal thermal decay of the strongest grating [Fig. 3(a)]. For this grating, lowering the reflectivity by 0.2% corresponds to a decrease of the refractive index modulation amplitude by 13%. It must be pointed out that the spectral quality of the gratings in transmission and reflection [Fig. 3(b)] is very good and corresponds to the expected shapes for gratings of uniform strength along their length. In particular, as noted above, the absence of features on the short wavelength side of the transmission spectrum indicates both very good alignment of the grating fringes perpendicular to the fiber axis, and very good

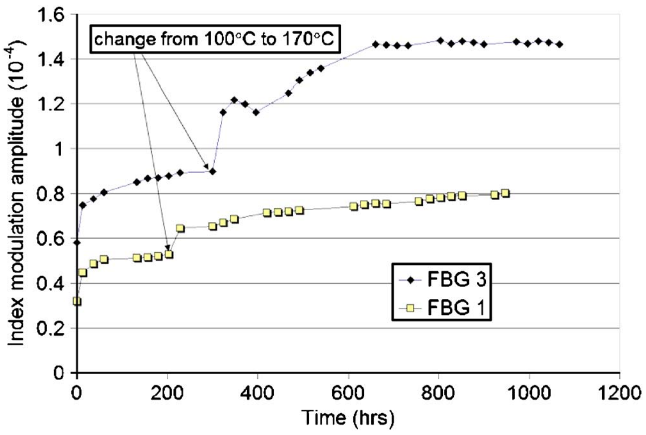

FIG. 2. (Color online) Grating growth during thermal treatment, first at 100 °C, then at 170 °C, for two different gratings: FBG 1, initial $R=52\%$ and FBG 3, initial $R=87\%$.

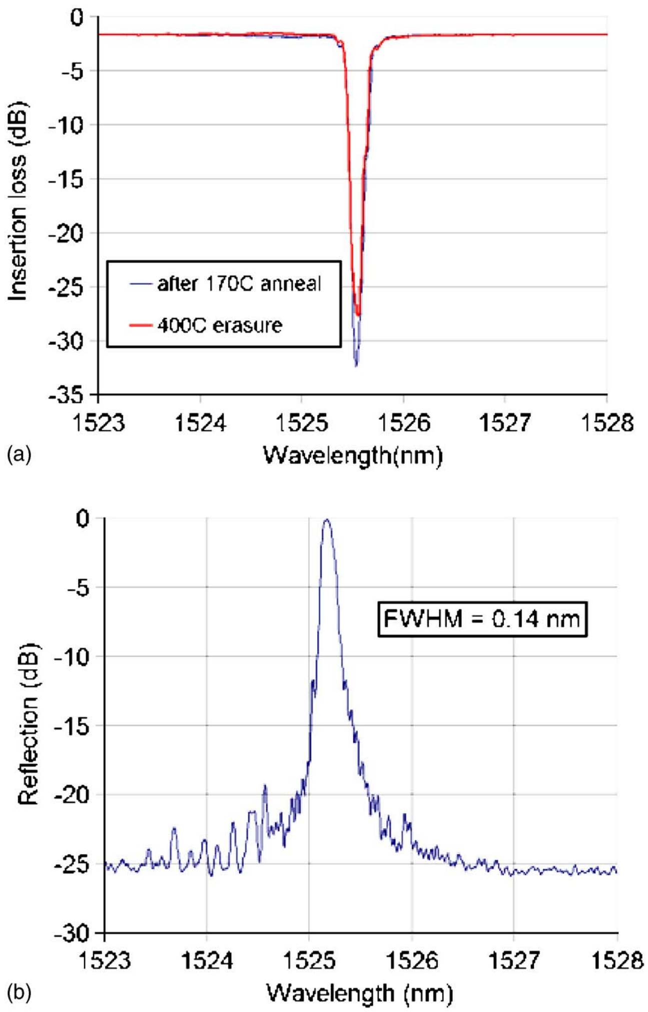

FIG. 3. (Color online) (a) Partial erasure of FBG 3: after a 1 min exposure to 400 °C the reflectivity decreases from 99.9% to 99.7%. (b) Final reflection spectrum of FBG 1 ($R_{\max}=96\%$).

uniformity of the fringe pattern across the depth of the fiber cross section.

The results are somewhat surprising in a few respects. Based on similar work in bulk phosphate glasses,[3,11] we would have expected too much absorption for useful photoinduced effects in the cores of these fibers. Also, the growth of the gratings during heat treatment has not been reported in other "classical" cases of silicate based photosensitive glasses, the exception being photothermorefractive glasses where silver is dissolved and holograms can be imprinted by exposing to interfering light beams but only revealed by subsequent heat treatment.[12] A possible explanation in the case of our fibers is that the UV irradiation strains the electronic bonds of the glass network in the bright parts of the interference pattern and that moderate heat allows some structural rearrangements in the strained regions, forming pairs of densified and dilated glass and hence a stronger refractive index modulation. This hypothesis is supported by the observation of UV light induced volume changes in bulk samples of similar glasses.[11] Furthermore, it is well known that phosphate glasses have a "softer" network structure to start with and it is possible that localized strain might be sufficient to lower the softening point enough to allow the proposed mechanism. Once the strain is released by glass rearrangement, the network would regain its original strength. The rather large apparent thermal stability of the heated gratings (very little decay at 400 °C) would support such a theory.

In summary, we have made Bragg gratings in phosphate glass single mode fibers with high reflectivity (99%) to form fiber laser cavities. The gratings actually become stronger with moderate heat treatment at 100 and 170 °C but eventually stabilize, an encouraging result for their long term reliability in normal operating conditions. Preliminary tests showed similar results in fibers made from the same materials but using microstructured cladding for optical mode confinement and also in fibers with rare-earth dopants (Er and Yb) in the core to provide gain in the *C* band. These results pave the way for the fabrication of short, monolithic cavity phosphate glass fiber lasers with improved spectral purity and stability and lower fabrication costs.

The authors are grateful to Y. Merzlyak, S. Yliniemi, and A. Laronche for technical assistance. Financial support for this project was provided by the Natural Sciences and Engineering Research Council of Canada, the U.S. Air Force Office of Scientific Research, the National Sciences Foundation, and the state of Arizona TRIF Photonics Initiative. One of the authors (J.A.) holds the Canada Research Chair in Advanced photonic components at Carleton University.

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