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Bragg gratings in Ce^{3+}-doped fibers written by a single excimer pulse

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Gratings with as high as 2.4% reflection efficiency written by a 20-ns single excimer pulse at 248 nm have been demonstrated for the first time to our knowledge in Ce^{3+}-doped fibers. The grating strength is shown to increase with Ce^{3+} concentration under the same writing conditions. Investigation of the grating decay at elevated temperatures has revealed several different time constants, showing that several different types of mechanism may be involved. Part of the grating was found to be stable for >10 h at 600°C.

The ability to write fine-period gratings into germanosilicate optical fibers by UV interferometry[1–3] has resulted in a surge of interest in fiber gratings as wavelength-selective components of optical-fiber systems. This is largely because of ease of manufacture and use but may also be attributed to the high quality (very low scattering loss) of these gratings compared with those manufactured by photoresist and etching techniques.

In germanosilicate fibers, the photoinduced refractive-index change when the fibers are exposed to blue light has been linked to the presence of oxygen-deficient GeO defects in the fiber core.[4,5] These defects are photoionized through two-photon absorption, and the released electrons are eventually trapped elsewhere in the glass. Single-photon absorption at UV wavelengths gives a much more rapid index change, the magnitude of which is related to the population of the GeO defects. Because this population depends critically on preform processing and fiber-drawing conditions,[6,7] its control is difficult to achieve during fabrication; to increase the photosensitivity, a large amount of germania has to be introduced into the fiber core to increase the GeO concentration, leading to fibers of high N.A. and causing undesirable high-insertion losses when the fibers are spliced into ordinary telecommunication fibers.

We studied Ce^{3+}-doped optical fibers with cores composed of SiO_2, P_2O_5, and Al_2O_3 to achieve more photosensitive fibers in a more controllable way.[8,9] Ce^{3+} ions, with an absorption band near 290 nm, can also be photoionized by UV radiation to release electrons to be trapped elsewhere and therefore undergo a similar process to that in a germanosilicate fiber. However, because the dopant responsible, Ce^{3+}, can be incorporated controllably into fibers with the well-developed solution-doping technique,[9] this approach has potential advantages over relying on the GeO population in germanosilicate fibers. Moreover, the few dopants required for a photoinduced index change of $\sim 10^{-5}$ in Ce^{3+}-doped fibers do not affect the refractive-index profile of the fiber.

After our first report on photosensitivity at UV wavelengths in germania-free Ce^{3+}-doped fibers,[8] Broer *et al.*[10] demonstrated a Bragg grating of 17% reflectivity after a 30-min exposure at 292 nm. We report what is to our knowledge the first production of Bragg reflectors in Ce^{3+}-doped fibers by interferometric exposure to a single 20-ns pulse at 248 nm from a KrF excimer laser (Lambda Physik Model EMG 150 MSC). The highest single-pulse grating efficiency reported in germanosilicate fibers is 65%.[3] The ability to write gratings with a single excimer pulse greatly relaxes the constraints on writing stability and makes the fiber-grating fabrication much easier and less time consuming. It is even potentially possible to write those gratings online immediately after the fiber is drawn and before it is jacketed. An investigation of grating decay at elevated temperatures has also revealed that several different mechanisms may be responsible for the photoinduced index change.

To write gratings, we focused the output of an excimer laser (0.1-J pulse with a duration of 20 ns and a beam size of 5 mm × 20 mm) onto the coating-stripped fibers by cylindrical lenses in an interferometric arrangement. The laser has a coherence length of 25 mm, and the focused beam had dimensions of approximately 0.3 mm × 20 mm. Four fibers of similar composition (SiO_2, P_2O_5, and Al_2O_3; see Ref. 8 for details) but different Ce^{3+} concentrations [0 to 11,700 ± 300 parts in 10^6 (ppm)] were tested. Care was taken to eliminate end-face reflections of the fibers in the grating measurements. The spectral response of a grating is shown in Fig. 1. The FWHM bandwidth of 0.15 nm in the figure is limited by the resolution of the optical spectrum analyzer. The gratings were written in the telecommunications window at 1550 nm, and their reflectivities were estimated with the 4% end-face reflection, measured with the same spectral resolution as used in measuring the grating, as a reference. Because the spectral bandwidth of the reflection from the gratings was narrower than that of the spectrum analyzer, we were effectively measuring the integrated reflection over the spectrum analyzer bandwidth. The single-frequency peak reflection from the gratings should be higher than the value that we measured. The

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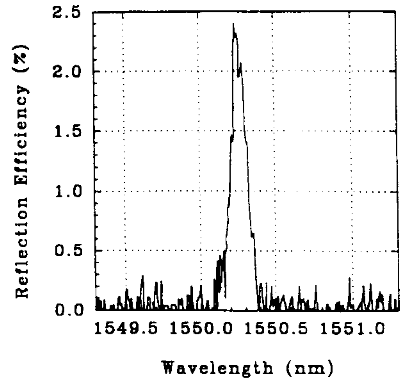

Fig. 1. Spectral response of a Ce^{3+}-doped fiber grating measured with a spectral resolution of 0.1 nm.

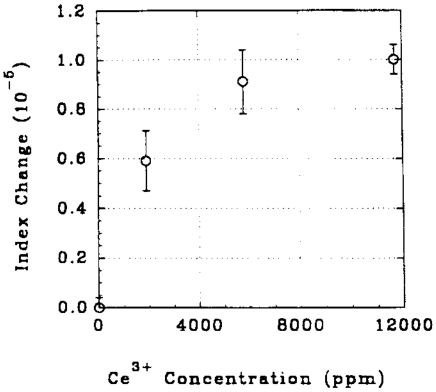

Fig. 2. Ce^{3+} concentration dependence of the induced index modulation in single-pulse gratings written under the same conditions.

profile of the gratings was similar to that of the gratings in germanosilicate fibers with similar reflectivities fabricated in our laboratory with the same setup. The fiber gratings were estimated to be 15 mm long from the 6-GHz FWHM measured in a germanosilicate fiber with a single-mode laser diode with temperature-tuned external gratings. We were then able to calculate the induced index modulation. The induced index modulation of gratings written under the same condition in the four fibers is shown in Fig. 2. No measurable grating was written in a fiber with no Ce^{3+} ions, and saturation is evident at high Ce^{3+} concentrations. The highest grating reflection of 2.4% was obtained in the fiber containing 11,700 ppm of Ce^{3+} ions.

The stability of the gratings was tested at elevated temperatures. The fiber with 11,700 ppm Ce^{3+} ions was used in these measurements. First a fresh grating placed inside a furnace and heated at a rate of 8 °C/min up to 700 °C, the peak reflection being monitored every 2 min with a spectrum analyzer set at 0.1-nm resolution (Fig. 3). A broadband light-emitting diode was used as the light source for this measurement. The reflection was found to decrease by a few percent even at temperatures as low as 150 °C. Another decay component was also noted at ~600 °C, where the reflection quickly decreased to just over 20% of its original level. We further characterized this second decay component by monitoring the time dependence of the reflection from fresh gratings at temperatures of 300, 400, 500, and 600 °C. A broadband light-emitting diode was again used, and the integrated reflection from the gratings was monitored continuously. The results are converted into induced index modulation and shown in Fig. 4. For the gratings tested at 300 and 600 °C (with ~1% initial reflections), the second decay component made up most of the reflection. When the grating writing conditions were slightly improved (because of better alignment of the writing interferometer), a more stable third component appeared (see curves at 400 and 500 °C in Fig. 4; initial reflections were >2%). The grating tested at 400 °C was actually monitored up to 2500 min (41.7 h) without further change. The stable component can account for >90% of the total index modulation (see curve at 500 °C in Fig. 4). The grating tested at 500 °C in Fig. 4 was further tested at 600 °C for >10 h without noticeable degradation. The same grating was finally heated from 600 to 1200 °C in 20 min and was found to disappear totally only at 1150 °C. To analyze the curves in Fig. 4, we assumed that the different writing conditions only vary the relative proportions of the three components and do not affect the decay rates of the components.

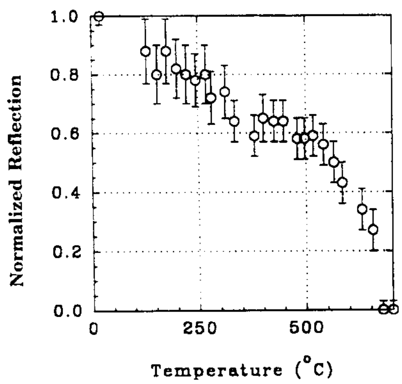

Fig. 3. Decay of the induced index modulation (normalized to an initial value of $\sim 5 \times 10^{-5}$) in a fresh grating (measured with 0.1-nm spectral resolution; grating bandwidth ~6 GHz) when heated at 8 °C/min up to 700 °C.

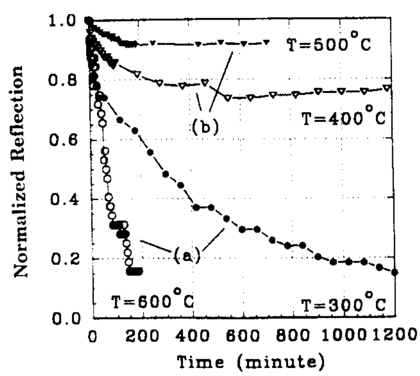

Fig. 4. Stability of the induced index modulations in Ce^{3+}-doped fiber at various temperatures measured by monitoring the integrated reflection [normalized to an initial value of approximately 3×10^{-5} for curves (a) and 5×10^{-5} for curves (b)] from the gratings. A broadband light-emitting diode was used as the light source. The grating writing interferometer was better aligned for the gratings in curves (b).

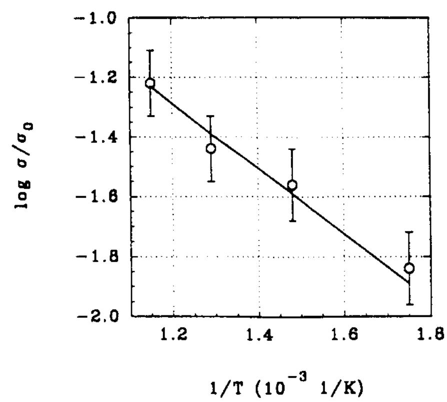

Fig. 5. Normalized decay rates against inverse of temperatures. The solid line is a theoretical fit of Eq. (1) obtained with $\sigma_0 = 2.1\ s^{-1}$ and $\Delta E = 2800\ cm^{-1}$ (0.35 eV).

The first component constituted only a small part of the total index modulation and was assumed to have totally recovered in the setting-up stage, which is not shown in Fig. 4. The third component was taken to remain stable at the tested temperatures. The curves in Fig. 4 were therefore fitted with the sum of an exponential decay component (second decay component) and a constant (third component); the decay rates of this second decay component were therefore obtained.

The normalized decay rates are plotted against the inverse of the temperatures in Fig. 5 and can be related to activation energy ΔE of the associated defect centers by

$$\sigma = \sigma_0 \exp\left(-\frac{\Delta E}{k_B T}\right), \qquad (1)$$

where σ_0 is the maximum decay rate at high temperatures and k_B is Boltzmann's constant. The activation energy of the second decay component is then obtained from the straight-line fitting of Eq. (1) in Fig. 5 to be 0.35 ± 0.13 eV (2800 ± 1000 cm^{-1}) and σ_0 to be ~2.1 s^{-1}. The decay rate at room temperature (T = 293 K) for this second component is deduced to be between several days and tens of days (the uncertainty is from the error in the decay-rate measurements). We previously observed that the UV-induced loss in Ce^{3+}-doped fibers recovers at different rates,[9] indicating that the photoelectrons are trapped at different types of defect center. The observation of different decay rates of the gratings may also be explained in that photoelectrons are trapped at several different sites, their release by thermal means having activation energies that are site dependent. We also observed that the gratings written with higher UV intensities (owing to better interferometric alignment) are much more stable than those written with lower UV intensities, indicating that the dominant mechanism responsible for the gratings varies with UV intensity. This provides further evidence that several different mechanisms may be involved in the process and that the contribution from each mechanism toward the ultimate index change depends on the grating writing conditions.

Meltz and Morey[11] reported that gratings in germanosilicate fibers started to decay at 300 °C and vanished at 900 °C. The recovering processes are therefore different in these two kinds of fiber owing to the different mechanisms involved. It seems clear that the Ce^{3+}-doped fibers offer an interesting alternative to germanosilicate fibers for fiber-grating applications. The gratings currently achieved in Ce^{3+}-doped fibers are useful for distributed sensor applications, where only a small reflection is required. The stable component of the gratings also makes them more attractive for temperature sensors. The reflectivity in these single-pulse gratings is likely to be limited by UV intensity in the core (much larger uniform index changes have been observed in these fibers[8]); we therefore expect to achieve higher reflectivity gratings in these fibers with better focusing of UV beam.

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