A technique for enhancing the thermal stability of hydrogen-loaded fiber Bragg grating

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Heat treatment with the presence of hydrogen (H_2) that react with GeE′ centers ($\cdot$Ge $\equiv$) at high temperature will weaken the refractive index modulation of grating fabricated in hydrogen-loaded normal germanosilicate fiber. Pre-annealing treatment of the above fiber was demonstrated to be able to enhance the grating's thermal stability effectively. 0.37-nm blue-shift of the reflected Bragg wavelength was observed.

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Fiber Bragg gratings (FBGs) based on the UV photosensitive germanosilicate fibers are often regarded as "permanent" structures. They have attracted considerable interest because they are useful in a wide range of applications in which wavelength selectivity is required. Unfortunately, standard telecommunications fibers where Bragg gratings are expected to have a strong applications impact are not photosensitive. Hydrogen-loading technique which soaked the fibers in high-pressure hydrogen to allow H_2 molecules to diffuse into the core of the fibers and made it possible to write gratings in normal GeO_2 doped fibers is commonly adopted[1,2]. However, the reflectivity of the H_2-loaded gratings will be gradually reduced as H_2 diffuse out from grating areas[3,4]. This diffusing process is highly temperature dependent. Therefore, the thermal stability is of prime importance if the H_2-loaded grating based components are expected to function properly over their required life and it is essential to find ways to stabilize it.

In this letter, we report the results of our experiments aimed at improving the thermal stability of H_2-loaded gratings.

The fiber used in our experiments was Corning SMF28. Before writing the FBGs, we placed it inside a temperature controlled hydrogen chamber for 48 hours. The pressure and temperature were set to 1600 psi and 70 °C, respectively. After H_2-loading, half of the fiber was then annealed using a temperature controlled furnace at ~ 120 °C for 1 hour and cooled under room temperature. This treatment occurred before writing the FBGs is called pre-annealing.

Phase-mask technique was used to fabricate the gratings in this experiment. The depth of the used 1-cm-long silica phase mask with period of 1072 nm has been optimized for writing with 193-nm wavelength laser beam. Lased from a COMPex205 excimer ArF laser, the UV writing beam was operated at 5-Hz repetition rate with a pulse energy of 60 mJ. It was partially focused onto the fiber through a 20-cm focal-length cylindrical lens. In order not to cause physical damage and form type II gratings, the illumination fluence was kept at ~550 mJ/cm^2/pulse. The polymer coating of the exposure area of the fiber had been stripped and the mask was placed close to the cladding. 1-cm-long FBGs with center wavelengths near 1558.5 nm have been fabricated in both H_2-loaded and pre-annealed H_2-loaded fibers by illuminating the fibers through the mask with the UV beam for 1.5 min.

The fabricated grating samples were characterized using a 1550-nm edge-emitting LED via a 3-dB coupler and the reflected wave was measured with an optical spectrum analyzer. The samples were placed inside the furnace to anneal and tested for thermal stability at temperature range from 20 to 450 °C.

Figure 1 shows the evolutions of the reflection spectra of the annealed gratings as a function of the temperature at which the gratings were elevated isochronally. The annealing time at each temperature was 1 hour. As shown

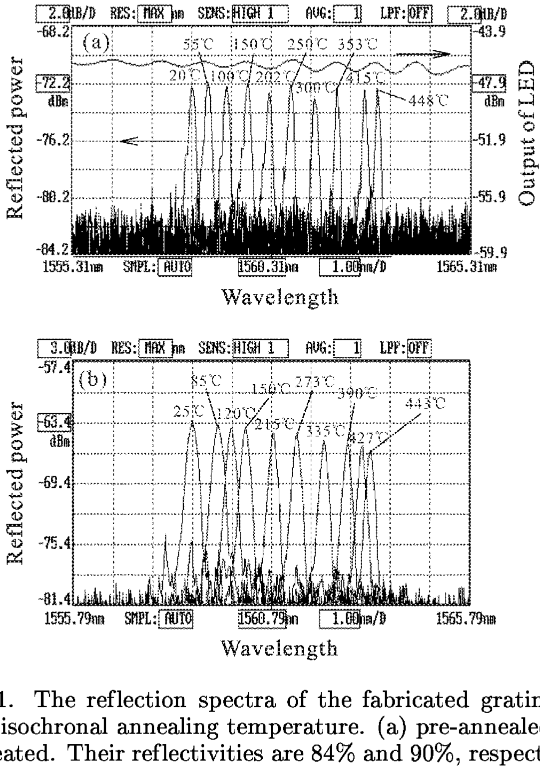

Fig. 1. The reflection spectra of the fabricated gratings at each isochronal annealing temperature. (a) pre-annealed; (b) untreated. Their reflectivities are 84% and 90%, respectively.

in Fig. 1(a), the reflectivity of the pre-annealed fiber grating almost kept at the same value of 84% within our experimental accuracy up to 448 °C. Obviously, this grating performs high-temperature stability characteristics. The little variation of the reflected power is due to uneven distribution of the LED output. The upper curve of Fig. 1(a) shows the spectrum of the LED. Whereas, for the untreated grating, shown in Fig. 1(b), a reduction of the reflection up to 3 dB was observed at the temperature of 443 °C. These demonstrated that the pre-annealing treatment is able to improve the thermal stability of H_2-loaded fiber grating.

Germanium defect centers are known to play a key role in the photosensitivity of germanosilicate fibers. However, when hydrogen is loaded into the fiber, the role of the defect centers is no longer clear. Ge–O bonds play the main role in the index change process instead. Excited by the UV light, the bonds are broken and then react with H_2 to produce OH groups and GeE′ centers (trapped hole with an oxygen vacancy)[5]

$$\begin{aligned} &\equiv \mathrm{Ge} - \mathrm{O} - \mathrm{Si} \equiv +h\nu \rightarrow \equiv \mathrm{Ge} - \cdots - \mathrm{O} - \mathrm{Si} \equiv, \\ &\equiv \mathrm{Ge} - \cdots - \mathrm{O} - \mathrm{Si} \equiv + \mathrm{H} - \mathrm{H} \rightarrow \\ &\equiv \mathrm{Ge} \cdot + \mathrm{H} - \mathrm{O} - \mathrm{Si} \equiv + \mathrm{H}\cdot, \end{aligned} \tag{1}$$

where $h\nu$ is the energy of the absorbed UV photon. The absorption presents at 6.35 or 5.1 eV (corresponding 195 and 241 nm, respectively) mainly[6,7]. Although a fraction of the atomic hydrogen might further react with the GeE′ center to form a Ge–H bond, most of the atomic hydrogen probably participates in breaking another Ge–O bond.

Most fibers show an increase in the population of the GeE′ centers after UV exposure[5,8]. The change in the population of the GeE′ causes changes in the UV absorption spectra, which lead to a refractive index modulation through the Kramers-Kronig relationship. This is the reason why FBG can be formed by exposure with the UV beam through the phase-mask.

If the FBG is annealed with the presence of H_2, it will react with the GeE′ as

$$\mathrm{GeE}' + 1/2\mathrm{H}_2 \rightarrow \mathrm{GeH}. \tag{2}$$

The temperature increase not only enhances the rate of the above reaction, but also accelerates the H_2 escape from the grating area. Both actions will weaken the formed index modulation[2]. The relationship between reflectivity R and the amplitude of the index perturbation Δn is given by[9]

$$R = \tanh^2 \frac{\pi \Delta n L}{\lambda_B} \eta, \tag{3}$$

where λ_B is Bragg wavelength, L is the grating length, and $\eta \approx 1 - 1/V^2$ is the fraction of the integrated fundamental mode intensity contained in the core. V is the normalized frequency of the fiber. At the wavelength of 1558.5 nm, the value of V of the fiber, with a core diameter of 8.3 μm and a numerical aperture (NA) of 0.14, is 2.34.

Reflection occurred in different areas of the grating was uneven. Contributions from the adjacent part (to the light source) of the grating are greater than that from the remote part. So, it is necessary to replace the grating length L, in Eq. (3), with an effective length L_{eff}. Eq. (3) becomes

$$R = \tanh^2 \frac{\pi \Delta n L_{\text{eff}}}{\lambda_B} \eta. \tag{4}$$

To a weak grating, $L_{\text{eff}} = L$, and to a heavy grating, $L_{\text{eff}} < L$. Figure 2 shows the relationship between the reflectivity and the amplitude of the refractive index perturbation for different L_{eff}.

For the reaction of GeE′ centers with H_2 above room temperature, from Fig. 2, it is reasonable to suggest that the reflectivity of FBG in H_2-loaded germanosilicate fibers can be reduced by heat treatment with the presence of H_2.

The pre-annealing treatment will decrease H_2 concentration in fiber core owing to the out-diffusion. With this fiber, the concentration of GeH in the annealed grating will be much smaller than GeE′ and therefore contributes negligibly to Δn.

Shown in Figs. 1 (a) and (b), the spectral widths of the annealed gratings get narrower with the increased temperature. It may be possible that the chirped part of the gratings formed by the UV induced innerstress

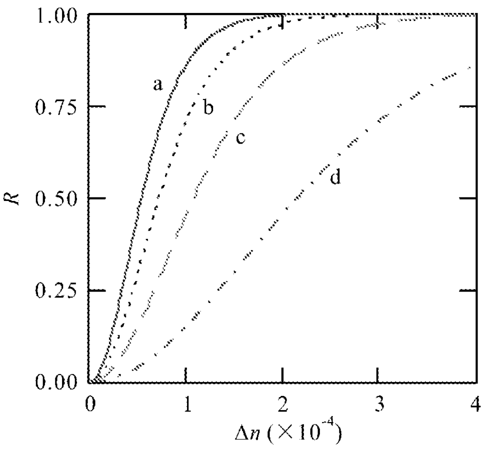

Fig. 2. R versus Δn for different L_{eff}. a: L_{eff}=10 mm, b: L_{eff}=7.5 mm, c: L_{eff}=5 mm, and d: L_{eff}=2.5 mm.

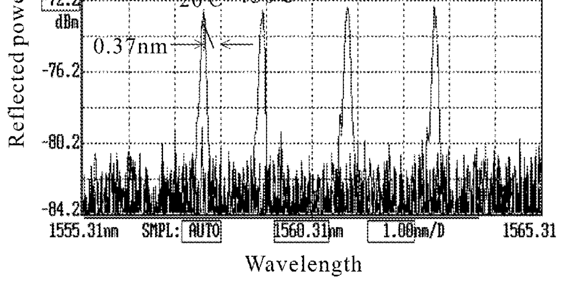

Fig. 3. Reflection spectra of the grating written in pre-annealed fiber recorded while the annealing temperature was decreased.

during fabrication was relieved under the high temperature. Another possible reason is the supersaturated state of the index modulation was palliated. For the untreated sample, the third reason is the index modulation was reduced. This part contribution is approximately proportional to the change of Δn[4].

The outer interface at zero H_2 concentration eventually allows the residue H_2 to diffuse out and the refractive index return to its "original" value. It turns out that the final value of λ_B is blue-shifted relative to the original wavelength. Together with the shift caused by the decay of GeE$'$ centers at high temperature, the blue shift of the pe-annealed FBG is 0.37 nm. Figure 3 shows the reflection spectra. It was recorded when the anneal temperature of the sample was decreased at the rate of 10 °C/min. The reason for the little reflection decay of the grating is its higher absorption at low temperature. A similar phenomenon has been observed by L. Dong *et al.*[7].

We have compared the thermal stability of FBG written in an untreated H_2-loaded standard telecommunication fiber to that written in a pre-annealed H_2-loaded sample of this fiber. Experiments demonstrated that the thermal stability of the H_2-loaded FBG can be enhanced by pre-annealing treatment. This technique will make FBG useful in fiber system operating in hostile environments.

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References

1. P. J. Lemaire, R. M. Atkins, V. Mizrahi, and W. A. Reed, Electron. Lett. **29,** 1191 (1991).
2. B. Malo, J. Albert, K. O. Hill, F. Bilodeau, and D. C. Johnson, Electron. Lett. **30,** 442 (1994).
3. S. R. Baker, H. N. Rourke, V. Baker, and D. Goodchild, J. Lightwave Technol. **15,** 1470 (1997).
4. H. Patrick, S. L. Gilbert, A. Lidgard, and M. D. Gallagher, J. Appl. Phys. **78,** 2940 (1995).
5. V. Grubsky, D. S. Starodubov, and J. Feinberg, Opt. Lett. **24,** 729 (1999).
6. R. M. Atkins and V. Mizrahi, Electron. Lett. **28,** 1743 (1992).
7. L. Dong, J. L. Archambault, L. Reekie, P. St. J. Russell, and D. N. Payne, Appl. Opt. **34,** 3436 (1995).
8. T. E. Tsai, G. M. Williams, and E. J. Friebele, Opt. Lett. **22,** 224 (1997)).
9. G. Meltz, W. W. Morey, and W. H. Glenn, Opt. Lett. **14,** 823 (1989).