Highly Stable Fiber Bragg Gratings Written in Hydrogen-Loaded Fiber

Bai-Ou Guan, Hwa-Yaw Tam, Xiao-Ming Tao, and Xiao-Yi Dong

***Abstract*—We demonstrated that the thermal stability of fiber Bragg gratings written in hydrogen-loaded standard fibers can be significantly enhanced by preirradiating the fiber with UV beam before writing gratings. Our experimental result shows that these gratings maintained more than 60% of their initial index modulation after 10 hours at 605 °C.**

***Index Terms*—Fabrication, fibre Bragg gratings, photosensitivity, thermal stability.**

I. Introduction

THERMAL stability of fiber Bragg gratings (FBGs) is of prime importance if grating-based components are to function properly over the required service life. The stability of FBGs at elevated temperature is a major issue in fiber-optic sensor that employs FBGs for measuring temperature. Investigations of the thermal decay of FBGs written in different types of fibers with and without hydrogen-loading were reported [1]–[3]. Regardless of the form of pretreatment a fiber has undergone to enhance its photosensitivity prior to writing grating, thermal decay occurs over time, even at room temperature [3]. This is because grating formation in fiber involves the excitation of glass into a metastable state. The extent to which this occurs depends on the fiber type, grating type, and the form of pretreatment used before writing the grating. The modulation index of a grating formed in hydrogen-loaded fiber decayed much faster than that in unloaded, high germanium-doped fiber under the same annealing condition [3]. High-temperature stable gratings ($>800\,^\circ$C) written in hydrogen-loaded germanium co-doped with fluoride was reported in [4]. Splicing of nonstandard high photosensitivity fiber to standard fiber introduces higher loss. Therefore, it is attractive to use standard telecommunication fibers for fabricating stable gratings because they are inexpensive and readily available. Unfortunately, nonhydrogenated standard fiber is not photosensitive enough, even at 193 nm.

Recently, Kohnke *et al.* reported a new photosensitization method by exposing hydrogen-loaded fiber to 248 nm UV uniform light prior to the grating writing process [5]. We have conducted an experimental investigation of the thermal stability of FBGs formed in pre-UV irradiated hydrogen loaded standard telecommunication fiber using 193-nm light. Our result demonstrated that gratings thus formed exhibit very high thermal stability.

Manuscript received March 6, 2000; revised June 15, 2000. This work was supported by the Hong Kong Research Grant Council under Competitive Earmarked Research Grant (Project PolyU 5123/97E).

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Publisher Item Identifier S 1041-1135(00)08604-3.

II. Experiment and Discussion

We used standard telecommunication fiber (Corning SMF-28) in our experiments. The fiber was hydrogen-loaded at 70 °C for five days at 140 atm. Before the grating writing process, some of the fiber were subjected to UV treatment by exposing directly to a uniform UV beam (i.e. without the phase mask) from a 193 nm excimer laser for about 5 minutes. The laser was operating at 157 mJ/cm^2/pulse and the repetition rate was 6 Hz. The fiber was then annealed for 12 h at 160 °C to remove any unreacted hydrogen. Finally, FBGs was written by exposing the UV-treated fiber sample to the UV beam through a phase mask. For comparison, several FBGs were also written in the hydrogen-loaded fiber that was not treated with the UV beam before writing the gratings. All gratings were written under the same exposure condition.

The annealing experiment was conducted by placing the gratings inside a temperature controllable oven (limited to about 600 °C). The gratings were annealed at 180 °C for 10 h, and their transmission spectrum was measured after they were cooled down to room temperature. The gratings were then returned to the oven, and the annealing process was repeated at a higher temperature. The peak reflectance R of the gratings was determined from the transmission spectrum. The index modulation amplitude $\Delta n_{\rm mod}$ was calculated from the peak reflectance R using the equation $\Delta n_{\rm mod} = \lambda \tanh^{-1}(\sqrt{R})/\pi L$ (λ is the wavelength at the peak reflectance and L is the grating length) [3].

Fig. 1 shows the relationship between the normalized index modulation $\Delta n_{\rm mod}/\Delta n_{\rm mod,0}$ ($\Delta n_{\rm mod,0}$ is the initial index modulation) and the annealing temperature for the treated and untreated FBGs. The experimental result clearly demonstrated that the treated grating is much more stable than the untreated gratings. For comparison, the annealing data of the FBGs written in hydrogen-loaded and unloaded highly germanium doped fiber by Patrick *et al.* [3] is also shown in Fig. 1. When the temperature is below 200 °C, the thermal stability of the treated FBG is slightly higher than the grating written in the unloaded germanium-doped fiber but much higher than that in the hydrogen-loaded fiber. The index modulation of the grating written in the unloaded high germanium content fiber reported in [3] was reduced by 5% at 174 °C, whereas the treated grating reduced by 3% after 10 h at 184 °C. When the temperature is

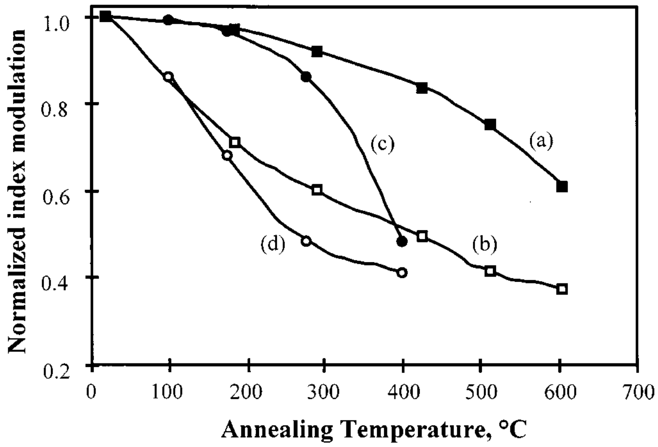

Fig. 1. Normalized index modulation of gratings after 10 h annealing as a function of annealing temperature. (a) UV treated hydrogen-loaded standard singlemode fiber (Corning SMF-28). (b) Untreated hydrogen-loaded standard singlemode fiber. (c) Highly germanium doped fiber: data taken from [3]. (d) Hydrogen-loaded highly germanium doped fiber: data taken from [3].

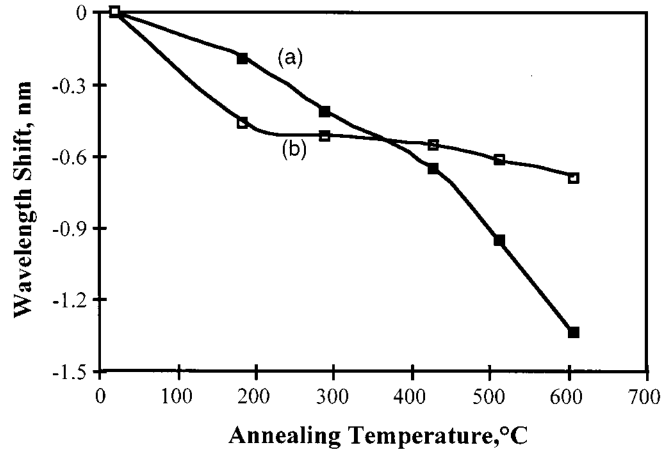

Fig. 2. Wavelength shift of the gratings measured at room temperature. (a) UV treated hydrogen-loaded standard singlemode fiber. (b) Untreated hydrogen-loaded standard singlemode fiber.

above 300 °C, the treated FBG exhibits much better thermal stability. For example, the index modulation in the treated FBG reduced by 16% after annealed at 426 °C for 10 h, whereas the unloaded high germanium-doped fiber reduced by 52% after 10 hours at 400 °C. Even after annealing at 605 °C for 10 h, the index modulation in the treated grating reduced by only 39%. Fig. 2 shows the wavelength shift of the gratings measured at room temperature after being subjected to different annealing temperatures. The initial large wavelength shift of the untreated grating was mainly due to the out-diffusion of hydrogen. The annealing temperature has a relatively small effect on the wavelength shift of the untreated grating. In the treated grating case, there is no hydrogen left in the fiber prior to writing grating. However, the wavelength shift of the treated grating has a strong dependence on the annealing temperature. A shift of 1.4 nm was measured after annealing at 600 °C for 10 h. Compared with the untreated grating, the DC component of the index of the treated grating decreased more, but its modulation index experienced a smaller reduction. It is interesting to note that even at 600 °C, the wavelength shift do not seems to reach "saturation." This feature could be used to "fine" tune the Bragg wavelength of a UV treated grating.

Fig. 3(a) and (b) show the growth behavior of the treated and untreated gratings. Both $\Delta n_{\rm mod}$ and $\Delta n_{\rm mean}$ (mean effective index change) of the treated grating increase monotonously with exposure time and can be described by an exponential function $\Delta n = at^{1/m}$, which is similar to that reported in [6]. $\Delta n_{\rm mod}$ and $\Delta n_{\rm mean}$ of the untreated grating follow an $\boldsymbol{S}$ shape function of exposure time [7]. The treated grating did not follow an $\boldsymbol{S}$ shape function because during the UV treatment, the fiber gone through the lower part of the $\boldsymbol{S}$ shape function. The UV pre-treatment also introduced larger mean index change Δn_{mean} in the treated grating. The precise reason that contributed to the high thermal stability of the treated grating is not clear. The UV treatment with the 193-nm light certainly help to remove the low activation energy defects and stabilized the grating. During the treatment process, the large absorption at 193-nm elevated

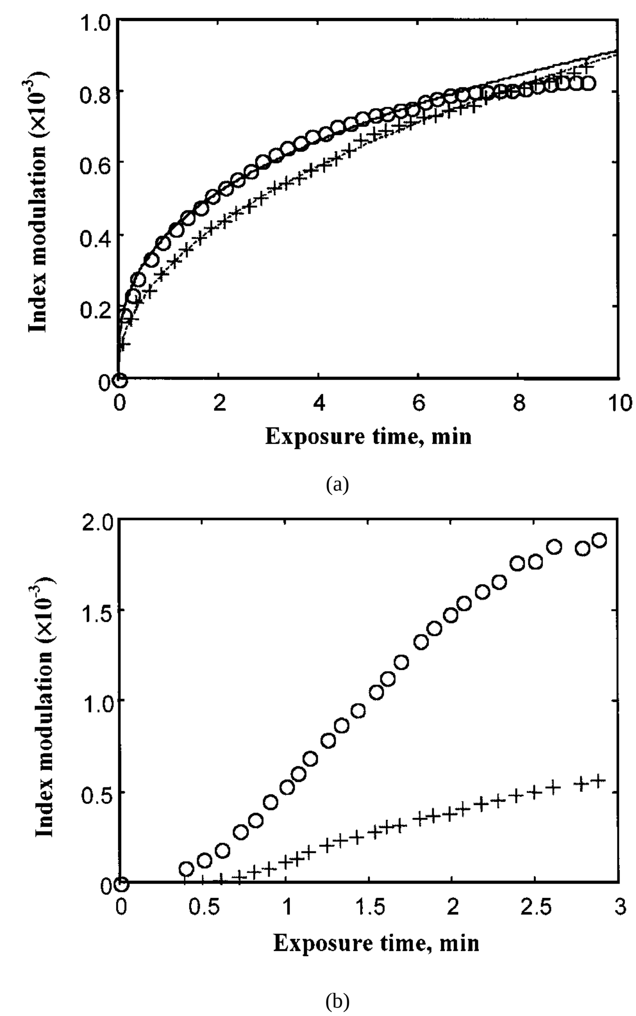

Fig. 3. (a) Growth behavior of the UV treated grating. The solid line and broken line are exponential fitting: $\Delta n_{\rm mod} = a_1 t^{1/m1}$, $a_1 = 4.03 \times 10^{-4}$, $m_1 = 2.82$; $\Delta n_{\rm mean} = a_1 t^{1/m2}$, $a_2 = 3.07 \times 10^{-4}$, $m_2 = 2.14$. (b) Experimental data for the growth of the grating in untreated hydrogen-loaded fiber. The circles and christcrosses represent the index modulation $\Delta n_{\rm mod}$ and mean index change $\Delta n_{\rm mean}$, respectively.

the core of the fiber to several hundred degrees centigrade. It is also important to note that the grating in the treated fiber was formed when the index change follows the upper part of the S shape function. This is the index change saturation region, and [8] reported that the change around the saturation region is more stable than that formed during the lower part of the S curve. The high reflection grating reported in [8] is not as stable as the gratings reported in this work. The mechanism that contributed to the high thermal stability of the UV treated grating may be different from that reported in [8] because the two techniques involved different writing conditions using excimer lasers of different wavelengths. The technique employed in this work allows the fabrication of low reflection but very stable gratings.

In conclusion, we have demonstrated that highly stable gratings can be written in hydrogen-loaded standard telecommunication fiber by prefabrication UV treatment. This type of grating is suitable for fabricating stable but low reflectivity (2% to 8%) wavelength lockers, for pump laser wavelength stabilization, and for sensor applications where operation at high temperature for long period is required. Our experimental result shows that these gratings maintained more than 60% of their initial index modulation after 10 h at 605 °C.

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