Postfabrication Wavelength Trimming of Fiber Bragg Gratings Written in H_2-Loaded Fibers

Bai-Ou Guan, Hwa-Yaw Tam, Chao Lu, and Xiao-Yi Dong

***Abstract*—A postfabrication technique for writing fiber Bragg gratings in H_2-loaded fiber with precise wavelength control is reported. The grating wavelength is highly stable and less than a 0.01-nm shift was observed after storing at room temperature for two months. This technique allows 1 nm of wavelength trimming and significantly enhances the grating thermal stability.**

***Index Terms*—Bragg gratings, fabrication, optical fibers, photosensitivity, thermal stability.**

I. Introduction

FIBER Bragg gratings (FBGs) have attracted considerable interest because of the large applications of grating-based devices in optical fiber communication and fiber sensor systems. FBGs are routinely fabricated in H_2-loaded fibers [1] as H_2 greatly enhances the fibers' photosensitivity. However, the diffusion of any unreacted H_2 molecules after grating formation leads to a shift in the Bragg wavelength [2]. The annealing process necessary for the stabilization of gratings also alters the Bragg wavelength. It is therefore difficult to predict the precise wavelength of the grating after annealing. Another problem with FBGs written in H_2-loaded fibers is that they have a rapid initial decay and are less stable than those written in photosensitive fibers (high Ge content) [3]. Such FBGs may not be suitable in certain sensing applications where the FBGs are subjected to high temperatures for long periods. A postfabrication technique to overcome these two problems is reported in this letter. By exposing an annealed FBG that was written in H_2-loaded fiber to a uniform UV beam, the grating wavelength can be precisely controlled with more than 1 nm of shift. This feature is particularly useful for DWDM application. In addition, the thermal stability of such FBGs is greatly improved and is much better than those written in unloaded fibers.

II. Experiments and Results

The fibers used in all the experiments are Corning SMF-28 fibers and were H_2-loaded at 70 °C and 140 atm for five days.

Manuscript received November 1, 2000; revised February 23, 2001. This work was supported in part by a grant from the Research Grants Council of Hong Kong, P. R. China, under Project PolyU 5123/97E.

B.-O. Guan and H.-Y. Tam are with the Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China.

C. Lu is with the Division of Communication Engineering, School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore 639798 Singapore.

X.-Y. Dong is with the Institute of Modern Optics, Nankai University, Tianjin 300071, China.

Publisher Item Identifier S 1041-1135(01)04560-8.

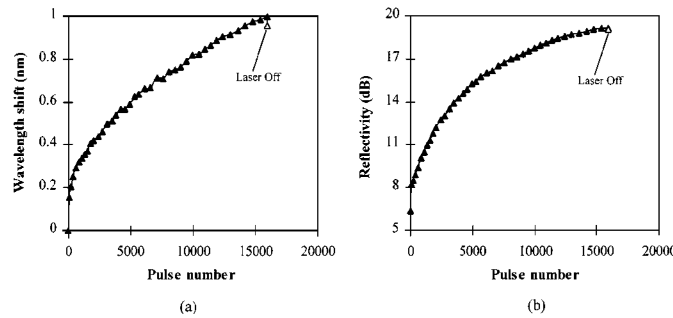

Fig. 1. (a) Bragg wavelength and (b) reflectivity of the post-UV-illuminated grating as a function of the number of excimer laser pulses.

An FBG was written in the loaded fiber using a 10-mm-long phase mask and a 193-nm excimer laser. The laser was operated at 128 mJ/cm^2/pulse with a repetition rate of 4 Hz. The FBG was annealed at 160 °C for 12 h to remove any unreacted H_2 and unstable UV-induced defects. The reflectivity of the annealed FBG was 6 dB. The grating was then exposed to a uniform UV beam. During the UV illumination process, the transmission spectrum was monitored with a light-emitting diode (LED) and an optical spectrum analyzer (OSA). Fig. 1(a) and (b) shows the Bragg wavelength and reflectivity, respectively, of the grating as a function of the number of laser pulses. As the UV exposure time to the grating increases, the Bragg wavelength shifts toward the longer wavelength and the reflectivity grows significantly. After 15 960 pulses, the Bragg wavelength increased by about 1 nm and the reflectivity grew from 6 to 19 dB, which corresponds to an increase of the mean index by 0.93×10^{-3} and an increase of the index modulation by as much as 215% (from 0.65×10^{-3} to 1.4×10^{-3}), respectively. This growth behavior is similar to the amplifications of the FBG in unloaded fiber by post-writing fringeless exposure with a 193-nm laser [4] and the long-period grating in hydrogen-loaded fiber exposed to a uniform UV beam at 248 nm [5]. This is a photosensitization process and can be explained by the two-step sensitization mechanism proposed by Canning [6]. In the two-step model, the photosensitization is described by $A \rightarrow B \rightarrow C$, in which the formation of B is aided or catalyzed by hydrogen, whereas the formation of C is independent of hydrogen. According to this model, UV exposure of hydrogen-loaded fiber could lock in enhanced photosensitivity permanently after the hydrogen's out-diffusion. This means that the bright fringe sections in the FBG were photosensitized after the UV inscription and annealing process, whereas the dark fringe sections after the annealing process are not photosensitive. Therefore, the bright fringe sections experienced a much larger increase in refractive index than the dark fringe sections during post-UV irradiation. As a result, the index modula-

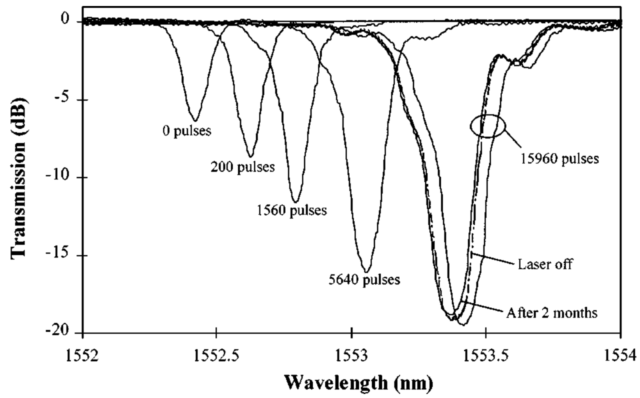

Fig. 2. Transmission spectra of the grating after exposure to different numbers of laser pulses. The spectrum of the grating after storage at room temperature for two months is also plotted in the figure.

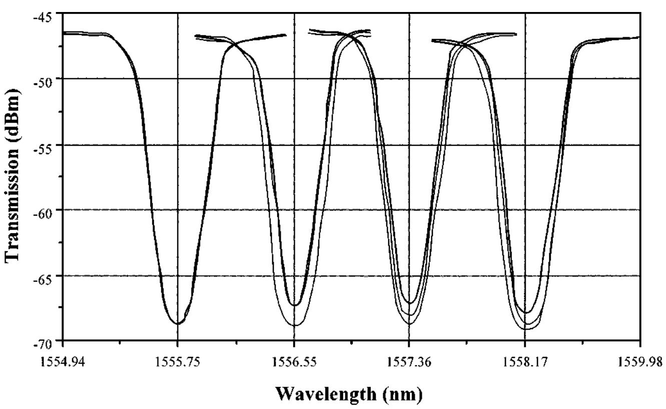

Fig. 3. Transmission spectra of the 11 gratings divided into four groups with their Bragg wavelength located at the ITU-grid.

tion will further increase, and hence the reflectivity of the FBG will grow.

The transmission spectra of the FBG after exposure to a different number of UV pulses are shown in Fig. 2. The small shift in the grating's Bragg wavelength (about 0.04 nm) toward the shorter wavelength immediately after the writing process is because the fiber temperature increases when it is exposed to UV light and drops to room temperature when the laser is switched off. The grating was stored at room temperature for two months and its wavelength was observed to change by less than 0.01 nm (limited by the resolution of the OSA). This demonstrates that the Bragg wavelength of the FBG after the UV illumination process is very stable. Zhang *et al.* [7] show that the Bragg wavelength of gratings fabricated with the phase mask technique can be tuned by prestraining the fiber during the writing process. However only 2–3 nm of tuning can be achieved because of the limitation of the mechanical strength of the fiber. Combining the prestraining technique with the post-UV illumination technique report here, the tuning range could be extended by 1 nm. The importance of this technique is that it allows the grating wavelength to be controlled very precisely by exposing the grating to the appropriate number of laser pulses. Fig. 3 shows the spectra of 11 gratings divided into four groups with their Bragg wavelength located at the ITU-grid. All the gratings were written in

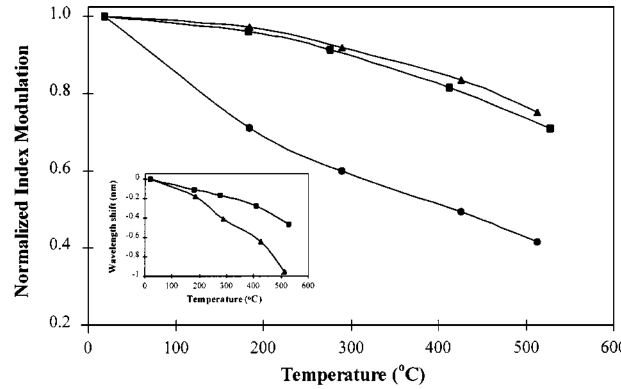

Fig. 4. Normalized index modulation of gratings after annealing at various temperatures for 10 h. The squares, circles, and triangles represent the post-UV-illuminated grating, a "normal" grating, and the grating in pre-UV irradiated H_2-loaded fiber reported in [8], respectively. Insert shows wavelength shift of the gratings after 10 h annealing. The squares and triangles represent the post-UV-illuminated grating and the grating in pre-UV irradiated fiber reported in [8], respectively.

H_2-loaded fiber using just one phase mask. The Bragg wavelength of the gratings was controlled by prestraining the fiber during the fabrication process follows by UV illumination.

We have shown in Fig. 2 that the reflectivity of the grating after post-UV illumination changes slightly after storage at room temperature for two months. The reflectivity of the grating decreased by only 0.36 dB, from 19.16 dB to 18.8 dB, which corresponds to 1.4% reduction in the index modulation. Patrick *et al.* [3] reported that gratings written in H_2-loaded fiber are not stable and the index modulation of such gratings could be reduced by more than 10% after two months at room temperature. To investigate the thermal stability of the grating after post-UV illumination at elevated temperature, an experiment was conducted by placing the grating and another "normal" grating (i.e., without post-UV illumination) inside a temperature controllable chamber. Both gratings were kept inside the chamber at a constant temperature for 10 h before they were removed and cooled to room temperature. The transmission spectrum of the gratings was then measured with a LED and an OSA. This process was repeated for different temperatures and the results are plotted in Fig. 4. The index modulation of the grating without going through the post-UV illumination process was reduced by 29% and 58% after 10 h of annealing at 183 °C and 513 °C, respectively. But the index modulation of the processed grating was reduced by only 4% and 29% after 10 h annealing at 183 °C and 528 °C, respectively. These results are also much better than the grating in unloaded Ge-doped fiber reported in [3], in which the gratings suffered a 52% reduction in index modulation after being annealed at 400 °C for 10 h. This strongly demonstrated that the post-UV illumination process greatly improved the grating thermal stability.

The authors have reported that the gratings written in pre-UV irradiated H_2-loaded fiber exhibit very high thermal stability [8]. For comparison, the annealing data for this kind of grating is also plotted in Fig. 4. The thermal stability of the post-UV treated grating is nearly identical to that written in pre-UV treated fiber. This similarity in the index modulation stability is expected because both processes involve fringe exposure and fringeless exposure (though in different order) of the H_2-loaded fiber to the UV light. These two processes both allow highly stable gratings to be made but the post-UV treatment permits precise trimming of the grating wavelength. In addition, the long-term wavelength stability of the gratings fabricated using the post-UV process is much higher. Insert of Fig. 4 shows the wavelength shift of these two kinds of gratings measured at room temperature after being subjected to different annealing temperatures. The wavelength of the grating in pre-UV treated fiber shifted 0.41 and 0.96 nm toward shorter wavelength after 10 h annealing at 290 °C and 513 °C, respectively. But the wavelength of the post-UV treated grating shifted only 0.17 and 0.46 nm, respectively, after 10 h annealing at 276 °C and 528 °C. The reason for this difference in the wavelength stability is still under investigation. We think that the large wavelength shift of the grating in pre-UV treated fiber may be due to the H_2-associated unstable UV-induced defects formed during prefringeless irradiation.

III. Conclusion

We reported a postfabrication technique that significantly enhances the thermal stability of gratings written in H_2-loaded fiber as well as permitting very precise control of the Bragg wavelength. The index modulation of such a grating was reduced by only 29% after 10 h annealing at 528 °C. The grating wavelength is highly stable and less than a 0.01-nm shift was observed after storiage at room temperature for two months.

References

[1] P. J. Lemaire, R. M. Atkins, V. Mizrahi, and W. A. Reed, "High pressure H_2 loading as a technique for achieving ultrahigh UK photosensitivity and thermal sensitivity in GeO_2 doped optical fibers," *Electron. Lett.*, vol. 29, no. 13, pp. 1191–1193, June 1993.

[2] B. Malo, J. Albert, K. O. Hill, F. Bilodeau, and D. C. Johnson, "Effective index drift from molecular hydrogen diffusion in hydrogen-loaded optical fibers and its effect on Bragg grating fabrication," *Electron. Lett.*, vol. 30, no. 5, pp. 442–444, Mar. 1994.

[3] H. Patrick, S. L. Gilbert, A. Lidgard, and M. D. Gallagher, "Annealing of Bragg gratings in hydrogen-loaded optical fiber," *J. Appl. Phys.*, vol. 78, no. 5, pp. 2940–2945, Sept. 1995.

[4] P. E. Dyer, R. J. Farley, R. Giedl, and K. C. Byron, "Amplification of fiber Bragg grating reflectivity by post-writing exposure with a 193 nm ArF laser," *Electron. Lett.*, vol. 30, no. 14, pp. 1133–1134, July 1994.

[5] G. E. Kohnke, D. W. Nightingale, P. G. Wigley, and C. R. Pollock, "Photosensitization of optical fiber by UV exposure of hydrogen loaded fiber," in *Optical Fiber Communication Int. Conf. Integrated Optics and Optical Fiber Communication*, San Diego, CA, 1999, pp. PD20-1–PD20-3.

[6] J. Canning, "Photosensitization and photostabilization of laser-induced index changes in optical fibers," *Optical Fiber Technol.*, vol. 6, pp. 275–289, July 2000.

[7] Q. Zhang, D. A. Brown, L. Reinhart, T. F. Morse, J. Q. Wang, and G. Xiao, "Tuning Bragg wavelength by writing gratings on prestrained fiber," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 839–841, July 1994.

[8] B. O. Guan, T. Y. Tam, X. M. Tao, and X. Y. Dong, "Highly stable fiber Bragg gratings written in hydrogen-loaded fiber," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1349–1351, Dec. 2000.