Fiber Bragg gratings with enhanced thermal stability by residual stress relaxation

Yuhua Li[1, 2], Minwei Yang[1], D. N. Wang[1,*], J. Lu[3], T. Sun[4] and K. T. V. Grattan[4]

[1] Department of Electrical Engineering, the Hong Kong Polytechnic University, Hong Kong
[2] Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China
[3] Department of Mechanical Engineering, the Hong Kong Polytechnic University, Hong Kong
[4] School of Engineering and Mathematical Sciences, City University, Northampton Square, London EC1V 0HB, U.K.
[*] eednwang@polyu.edu.hk

Abstract: Fiber Bragg gratings with greatly enhanced thermal stability have been fabricated by the use of femtosecond laser pulse irradiation on optical fibers with relaxed residual stress, through using high temperature annealing treatment. The grating reflectivity and resonant wavelength can be maintained for periods up to 20 hours using isothermal measurements and temperatures up to 1200 °C. No hysteresis was observed in the wavelength response when the gratings were annealed and the temperature cycled repeatedly between room temperature and 1200 ºC.

OCIS codes: (120.6780) temperature; (060.7140) Ultrafast processes in fibers; (060.3735) Fiber Bragg gratings.

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1. Introduction

Fiber Bragg grating (FBG) devices used for high power fiber laser systems and optical fiber sensors in harsh environments often need to be able to survive very high temperatures [1-3]. Although the FBG is usually referred to a 'permanent' refractive index modulation in the fiber core, exposure to a high-temperature environment may result in the bleaching of the refractive index modulation that forms the grating. The maximum temperature a conventional FBG (used for example in temperature sensors) can sustain is typically reported to be around 600 ºC, this arising due to the weakness of the germanium and oxygen bonds [4]. Many research projects have been undertaken to aim to increase the thermal stability of these grating structures, for example through experiments involving accelerated aging, pre-irradiation, the formation of type II gratings, specialist ion-doped fibers and the use of chemical composition fibers, etc. [5-9]. However, a level of reflectivity decay of the grating that is unacceptable for many sensor purposes is still seen to exist at elevated temperatures and thus high temperature sensors cannot be developed. Recently, regenerated gratings have been produced in B/Ge-doped fiber, which can sustain high temperatures, of over 1200 ºC [10, 11]. However, specially doped fiber is required for this type of grating inscription and hydrogen loading of the fiber is also required [10]. In the last few years, FBGs fabricated by use of femtosecond laser pulses have attracted considerable attention in research and the thermal stability tests show that femtosecond laser inscribed type II-IR FBGs exhibit excellent stability, at temperatures slightly in excess of 1000 ºC [12-13]. This is likely to be the result of a nonlinear self-focusing process where ultra high peak power locally affects the glass structure [2, 14]. However, good thermal stability cannot be maintained when the temperature is increased to 1100 °C or higher [12-13] and the gratings then rapidly decay. One of the limitations to achieving an improvement in thermal stability lies in the fact that the residual stress exists in all optical fibers during their formation process, which has negative effects on the fiber reliability and grating quality and consequent thermal stability. The residual stress results mainly from the superposition of the thermal stress, caused by the difference in thermal expansion coefficients between the fiber core and the cladding, and the mechanical stress induced by the difference in the viscoelastic properties of the two regions [15].

In this paper, results on the characteristics of femtosecond laser pulse-induced type II-IR FBGs written in non-hydrogenated SMF-28 fibers with relaxed residual stress through use of an annealing treatment at high temperature are presented. Such gratings exhibit excellent thermal stability at temperatures up to 1200 °C, showing a grating reflectivity and a resonant wavelength that are essentially unchanged for 20 hours, during the isothermal measurements. Moreover, the gratings written in this work have a clear potential to maintain a high thermal stability at temperatures above 1200 °C, which makes them attractive as sensing elements for monitoring applications where very high temperatures are experienced.

2. Experimental setup and results

The SMF-28 fibers used and into which the gratings to be inscribed were first annealed in an ISOTHERMAL PEGASUS ^{PLUS} 1200 tube furnace at temperatures of 800 ºC and 1100 ºC respectively for about 5 hours, in order to relax the residual stress in the fiber. The grating inscription was performed by use of a Ti: sapphire laser system (Spectral Physics): it consists of an oscillator (Mai Tai) and an amplifier (Spitfire Pro). The amplified laser system emits pulses of 120 fs with linearly polarized light at a central wavelength of approximately 800 nm (TEM_{00} spatial mode, repetition rate of 1 kHz) and a $1/e$ Gaussian beam radius of $\omega_0 = 2mm$. The maximum pulse energy of the laser output was ~1 mJ, which could be attenuated as required by rotating a half waveplate followed by a linear polarizer. The laser beam was then focused using a cylindrical lens with a focal length of 60 mm through a silica phase mask into the fiber core region. Assuming Gaussian beam optics, the width of the focal spot size was determined to be $7.6\mu m$. The phase mask used (Ibsen Photonics) in the experiments was optimized for 800 nm illumination (having a grating pitch of 1070nm and the first-order diffraction efficiency of 72.8 %). After the annealing treatment, the fiber became substantially

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brittle. However, it is not particularly difficult to inscribe the grating on such a fiber as long as a careful attention is paid to the process. In order to ensure an efficient inscription of the grating, the fiber was positioned in close proximity to the phase mask (~300 μm) by use of a high-precision four-axis translation stage and the laser focus was adjusted in a way that allowed the beam to enter the fiber core, thus to ensure efficient inscription of the grating.

The thermal stability properties of the gratings thus fabricated were studied by inserting the fiber containing the grating into the tube furnace mentioned above, allowing for a temperature range between 150 and 1200 ºC to be explored (with a stability of between ± 0.05 ºC at the low temperatures and ± 0.2 ºC at the upper end, respectively). The annealing test was performed under ambient conditions in air, and the reflection spectrum of the grating, monitored during the annealing process, was measured by use of a super wideband light source (Amonics ALS-CWDM-FA) and an optical spectrum analyzer (YOKOGAWA AQ6319) with a maximum resolution of 0.02 nm.

A number of type II (damage) FBGs were inscribed in the pre-annealed SMF-28 fibers using a pulse energy of 550 μJ and a 2~3 min exposure time. In the experiments carried out, the thermal stability of the FBGs fabricated in the pre-annealed fibers at a temperature of 800 ºC was characterized by the isochronal annealing approach and the results were compared with those for FBGs written in fibers without using the pre-annealing treatment, but under the same inscription conditions. Figure 1 shows the variation of the reflectivity when the fibers were subjected to short-term thermal exposures (~30 min at each temperature) to 100 °C, 200 °C and then progressively to 1200 °C, with a temperature increment of 100 °C. When the temperature is increased, it was observed that the FBGs written in both types of fibers were thermally stable at temperatures of up to 1000 °C, above which a portion (about 20%) of the refractive index change was annealed out for those gratings written in the fibers without the pre-annealing treatment, resulting in a degradation of the grating reflectivity from 10.04 to 8.05 dB within a few minutes, when the temperature was allowed to reach 1200 ºC. On the contrary, the FBGs created in those fibers which had the pre-annealing treatment could readily sustain temperatures higher than 1000 ºC, with 95 % of its initial reflectivity remaining and showing an almost negligible decay rate after a 30 min exposure at a temperature of 1200 ºC. This experiment was able to show the enhanced short-term thermal stability that was achieved.

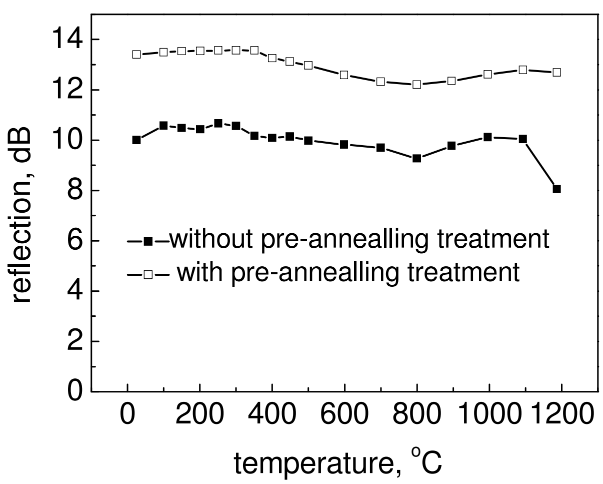

Fig. 1. Comparison of the short-term annealing characteristics of gratings written in pre-annealed and non-annealed fibers.

The short-term annealing tests described above show that the type II-IR gratings written in the pre-annealed SMF-28 fibers are extremely stable at temperatures below 1200 ºC. A long-term thermal stability test on these type II-IR gratings was also carried out by heating the

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gratings to 1200 ºC, then keeping them at that temperature for about 20 hrs, monitoring the change in the grating reflectivity (Fig. 2) and the resonant wavelength (Fig. 3) respectively. It can be observed from Fig. 2 that the gratings written in the pre-annealed fibers (either at 800 ºC or 1100 ºC) exhibit a clearly enhanced thermal stability. While the type II FBGs created by the femtosecond pulses in the non-annealed fibers were almost “washed out” after an exposure of about 400 min at a temperature of 1200 ºC, the type II FBGs written in the pre-annealed fibers revealed an ultra-high thermal stability. The gratings written in the pre-annealed fibers at 800 ºC have a slow decay rate and the reflectivity decreases by only ~2.44 dB after 700 min duration of the annealing process (about 0.21 dB/hour). It can also be noted that the type II-IR gratings written in the pre-annealed fibers at 1100 ºC were almost unaffected by the thermal exposure to temperatures up to 1200 ºC and there was only a slight degradation of the grating strength over the duration of the test. When compared with the work reported previously [9, 10], the results of our experiments have shown that the stability of the gratings has substantially increased, at the high temperature. Type II-IR gratings are created when the laser intensity is greater than the damage threshold for the particular glass and the ultra high temperature stability obtained is due to the ultra stable grating structure formed. It is believed that the stability of the grating structure is related to the way it forms - for example when using a long pulse UV laser or a femtosecond IR laser, and it also depends on the residual stress of the fiber glass during the grating formation. The thermal stability of the FBG can thus be improved by relaxing the residual stress in the fiber before the grating inscription is commenced.

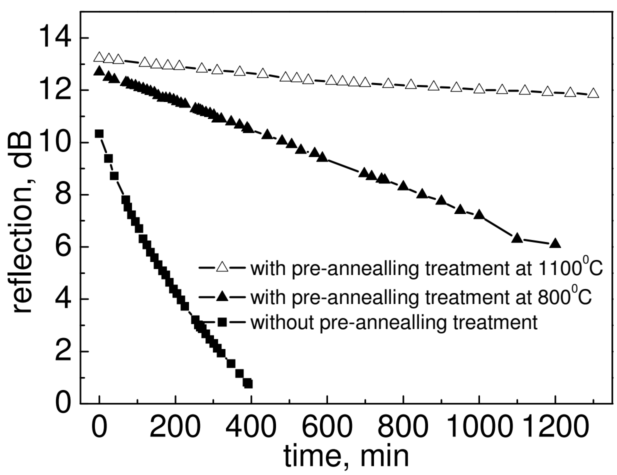

Fig. 2. Change in the reflectivity of the type II-IR FBGs inscribed in normal and pre-annealed fibers over a 1300 min period at an annealing temperature of 1200 ºC.

In the experiments carried out, the resonance wavelength was also measured every ten minutes or so during the annealing process. The gratings in both the normal fibers and the pre-annealed fibers at 800 ºC showed a slow shift, with the annealing time, towards the shorter wavelength region (as shown in Figs. 3(a) and (b)), which coincided with the grating decay. However, the shift was not monotonic and fluctuations in the resonance wavelength were observed during the annealing process, as reported previously [12-13]. For the gratings written in the pre-annealed fibers at 1100 ºC, the resonance wavelength showed a slight fluctuation at the beginning of the test. After 100 minutes or so, the resonance wavelength became essentially constant at 1585.16 nm at a temperature of 1200ºC (with a variation of less than the resolution limit of the optical spectrum analyzer used) regardless of the annealing time at 1200 ºC, as shown in Fig. 3(c). It seems apparent that the resonance wavelength is related to the effective index and the grating period, both of which change with the temperature, thus leading to the fluctuations seen.

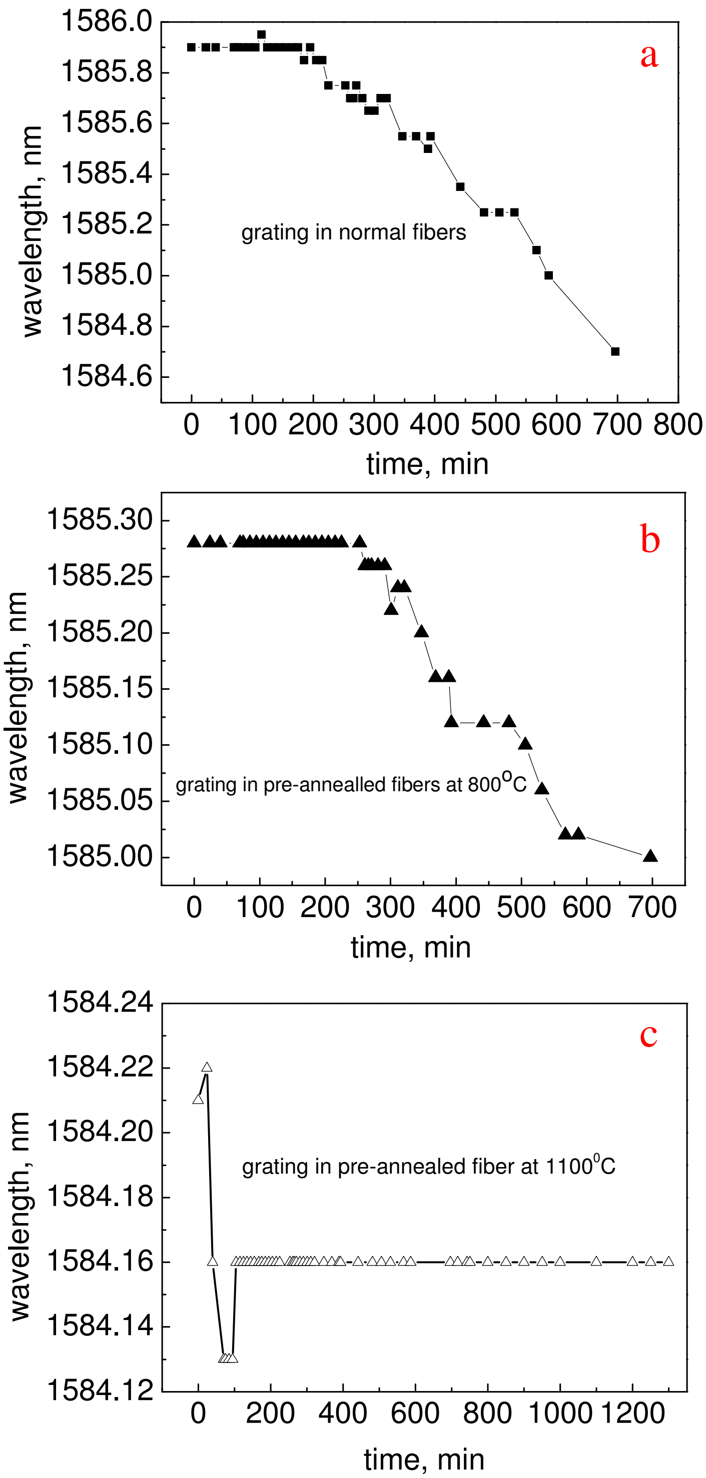

Fig. 3. Change in the resonant wavelength of the type II-IR FBGs inscribed in (a) normal fiber; pre-annealed fiber at (b) 800 ºC; and (c) 1100 ºC over a period of 1300 min at an annealing temperature of 1200 ºC.

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Following the long-term high temperature annealing tests, the femtosecond induced fiber gratings were cycled from room temperature to 1200 ºC several times in order to examine the repeatability of the measurement for potential sensor applications. The grating was further annealed for about 10 hours and the temperature was again cycled to 1200 ºC from room temperature and back, and the resonant wavelength observed was plotted against temperature in each case (as shown in Fig. 4). Two such cycles were observed and the change on the resonant wavelength was seen to be repeatable with no hysteresis being observed during the tests.

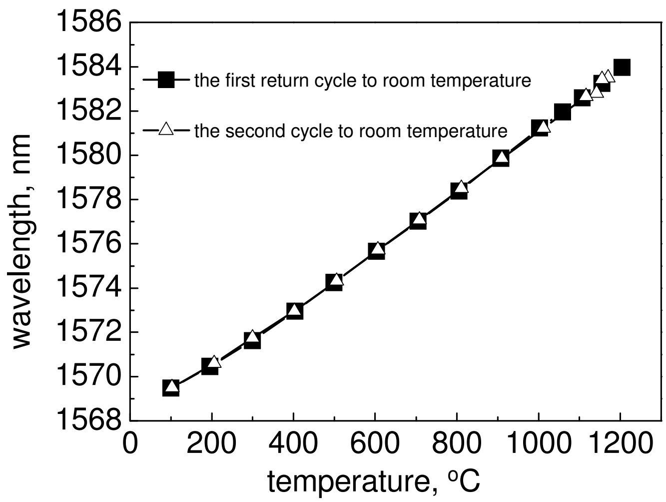

Fig. 4. Temperature cycling of the type II-IR FBGs written in pre-annealed SMF-28 fiber at 1100 ºC.

3. Conclusion

In conclusion, FBGs have been successfully fabricated by use of IR femtosecond laser pulses in SMF-28 fibers with the use of pre-annealing treatment at the high temperature in order to relax their residual stress. The annealing test results demonstrate that the FBGs developed in this work exhibit extremely high thermal stability, this representing an improvement on previous work. Measurements of the grating reflectivity and the resonant wavelength can be maintained for 20 hours through isothermal measurements at temperatures up to 1200 °C. Moreover, such gratings have significant potential to sustain temperatures higher than 1200 °C, which makes them attractive for many high temperature sensor applications, such as for aeroengine monitoring.

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