

# Thermal stability of fiber Bragg gratings in different fibers

P. SAIDI REDDY, R. L. N SAI PRASAD\*, D. SENGUPTA, M. SAI SHANKAR, K. SRIMANNARAYANA  
*Department of Physics, National Institute of Technology, Waranagal-506 004, India*

Thermal stability and temperature response are very important parameters for fiber Bragg gratings (FBG) to be used as sensors in high temperature applications. Experimental and theoretical analysis of the thermal erasure dynamics and temperature response of FBGs written in hydrogen-loaded and non hydrogen loaded photosensitive fibers has been carried out in the present investigation. The sensitivity and the behavior of wavelength shift of the gratings over the temperature range of 35°C to 1075°C are studied and reported. The regenerative property and anomalous behavior of the gratings were also studied.

(Received November 11, 2009; accepted November 23, 2009)

*Keywords:* Fiber Bragg grating, Erasure dynamics, Regeneration, Thermal stability

## 1. Introduction

In the area of fiber optic sensors, FBG sensors have proven to be very successful as substitutes for the traditional fiber based sensors. Their small size and inconspicuous presence are very promising in applications that also require the physical advantages that come with optical fibers such as, EMI immunity, distributed sensing, light weight, radiation and corrosion tolerance. In addition, FBGs have unique optical advantages to offer such as immunity to intensity fluctuations, polarization changes, and connection losses. These merits arise from the fact that it is a self-referenced linear device in which the information is wavelength-encoded.

This temperature sensor is used in high temperature environment. Here, the choice of the grating type and the type of refractive index modification technique is of great relevance. In general, FBGs are classified into two types; Type- I and Type – II. Type-I grating results from color centre change and the related modification of the absorption spectrum is described by the Kramers Kronig [1] relation. The temperature behavior of this type of grating was analyzed by Erdogan et.al [2] up to a maximum operating temperature of 450°C. The Type - II gratings [3] are generated by using intensities near the damage threshold of the doped glass. In this type, refractive index modification is caused as stress disappears near the transition temperature of the core glass. Type II gratings show high loss in the lower wavelength range. Another class of gratings called Type-II A are in between Type I and Type II gratings with respect to their temperature stability. Grating stabilities under temperatures up to around 500°C are reported and these gratings are observed to have a refractive index change [4].

Thermal stability of FBG is of prime importance at elevated temperatures since grating-based components have to function properly over the required service life for measuring temperature. Investigations on stability of

FBGs made up of fibers with and without hydrogen loading for different dopants like Boron, Nitrogen, Fluorine, silica, Chlorine, Titanium, Germanium, Tin, Tantalum and Lead etc. have been carried out by various research groups [5-7].

Micheal Fokine was the first to invent fluorine doped [8] and Oxygen-modulated [9] Chemical Composition Gratings (CCG). These gratings written in standard telecommunication fiber were shown to withstand more than 1000°C. These gratings have a diffusion-controlled decay behavior with more than 50% of the reflectivity remaining after 7.5 hours at a temperature of 1230°C.

Experimental studies have been carried out on the thermal stability of the gratings with and without hydrogen loading in this investigation. Seed gratings of Type-I written in Boron co-doped Germanosilicate fiber with hydrogen loading, processed at temperature of approximately 1100°C are used for the study of hydrogen loaded fibers and SM1500 boron-germanium doped fiber (4.2/80µm) has been used for the study of non hydrogen loaded fiber. It has been observed that there is some disagreement in thermal stability and regeneration properties of the gratings written in hydrogen loaded and non hydrogen loaded fibers.

## 2. Experimental setup and discussion

The schematic of the experimental setup for thermal erasure dynamics and regenerative properties of gratings with hydrogen loaded and non hydrogen loaded FBGs is shown in Fig.1. In the experimental setup, the FBG sensor is inserted in ceramic tube which is then placed axially at the center of a cylindrical Inductive Coil Furnace (ICF). The furnace temperature,  $T$ , can be ramped up/down in the range  $25^{\circ}\text{C} < T < 1100^{\circ}\text{C}$  by controlling the current ( $I$ ) flowing through the coils. A Super Luminescent Diode (SLD) broadband source (C-Band: 1524nm-1572nm) connected to port-1 of a 3-port fiber optic circulator is

used to launch light into the grating-inscribed fiber which is connected to port-2 of the circulator. The light reflected from the grating is redirected into the OSA (ANRITSU with 10pm resolution) connected to port-3.

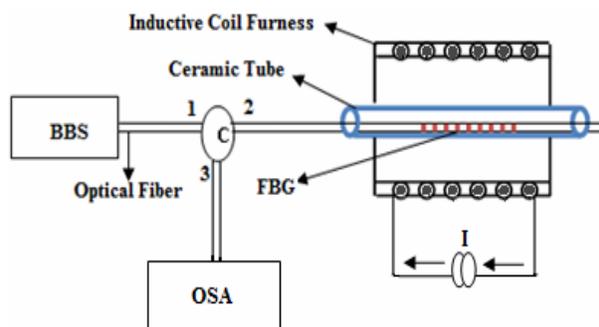


Fig. 1. Schematic of experimental setup.

## 2.1 Characteristics of FBG without hydrogen loading

The FBG was inscribed in Fiber core SM1500 (4.2/80 $\mu$ m) using phase mask technique. The fiber was placed in close proximity of Bragg Photonics phase-mask with a period  $\Lambda_{pm} = 1058$ nm. A Braggstar industrial Line Narrow Excimer laser (248nm) with a pulse energy of 2.56 mJ at 200 hz and having a spatial coherence of 1.5 mm along fiber axis was used to write 3mm long grating. The grating with 90% reflectivity and Bragg wavelength  $\lambda_B$  at 1535.8 nm was formed within 30 seconds of exposure.

The Bragg grating ( $\lambda_B = 1535.8$ nm) in the fiber was thermally treated in the temperature range  $35^\circ\text{C} < T < 850^\circ\text{C}$  over a span of 3 hrs, and the reflected Bragg peak at each temperature was noted. During this erasure process, a new peak was observed on the longer wavelength side of the spectrum [10]. This new peak has shown most anomalous behavior in the temperature range of  $35^\circ\text{C} < T < 650^\circ\text{C}$ . During this temperature range, it was observed that the new peak as well as the old Bragg reflected peaks repeat with irregular periodicity. This Temperature range is defined as the anomalous regime. Whereas in the temperature range  $650^\circ\text{C} < T < 825^\circ\text{C}$ , the reflected peak is periodic with no anomalous behavior. As temperature increases the reflected peak power is constant up to  $400^\circ\text{C}$  and after words the reflected peak power has exponentially decreased upto  $825^\circ\text{C}$  and the grating has erased [11]. The overall temperature sensitivity of the grating was noted to be 13.45 pm/ $^\circ\text{C}$  until a complete erasure of the grating occurred at  $T = 850^\circ\text{C}$  as shown in Fig. 2. These discontinuities can be attributed to the periodic growth and influence of thermal stress. The effective refractive index ( $n_{eff}$ ) of the fiber is dependent on the refractive index of both core and cladding. As the core and cladding materials are different, there will be a mismatch in the thermal

expansion at the core-cladding interface. This induces a thermal stress on the core. As a result, anomalous split in the peak is formed depending on the stress. Also, as temperature rises  $\lambda_B$  also increases linearly up to  $825^\circ\text{C}$ . Beyond this temperature,  $\lambda_B$  is constant and reflected peak power reaches to zero i.e. the grating is completely erased.

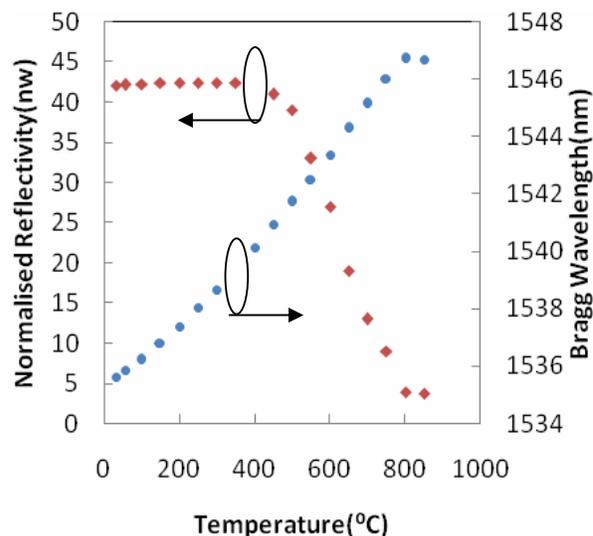


Fig.2. Typical dynamics of the reflectivity of non hydrogenated FBG.

## 2.2 Characteristics of FBG with hydrogen loading

Boron-Germanium doped silica fiber (core: 20 mol. % B, ~33 mol. %  $\text{GeO}_2$ ; inner cladding: ~11 mol. % P, ~4 mol. % F) is used in this experiment. Boron is added to lower the refractive index of high concentration germanate doped core to match the standard telecommunications fiber while making the fiber highly photosensitive. The fiber was then kept in hydrogen chamber at 180 atm. pressure for 24 hrs while it is placed under tension with a standard load ~100g. Type-I Grating ( $L = 5$ mm) has been inscribed in it by using an ArF exciplex laser (193nm,  $\tau_w = 15$ ns,  $f_{pulse} = 40-70$  mJ/ $\text{cm}^2$ , repetition rate = 10Hz,  $f_{cumulative} = 360$  J/ $\text{cm}^2$ ). An ultrahigh-temperature micro heater (Hot zone  $L = 10$ mm) was used for annealing the grating which was under tension with a load of 85g [12]. The process temperature was monitored using a thermocouple calibrated with data supplied by the manufacturer and also against the Bragg wavelength,  $\lambda_B$ , of the grating. An optical spectrum analyzer is used to analyze the characteristics of the grating. Regenerated grating was observed due to hydrogen loading which suggests that hydrogen plays a critical role, most likely through the formation of OH ions. The transmission spectra of the Regenerated Fiber Bragg grating is shown in Fig.3.

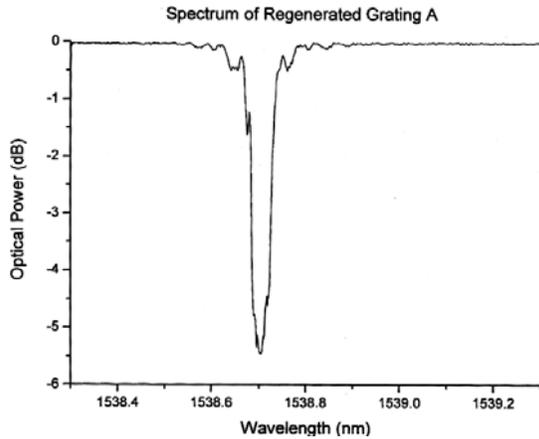


Fig. 3. Typical transmission spectra of the regenerated fiber Bragg grating.

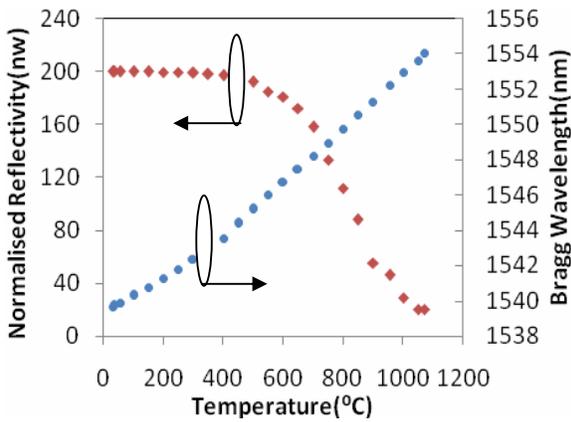
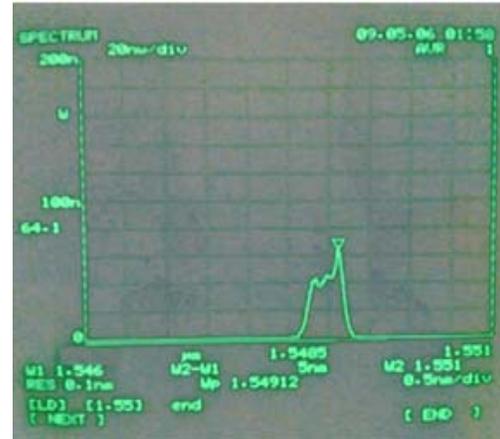


Fig. 4. Typical dynamics of reflectivity of the hydrogen loaded FBG.

In the experimental setup the grating has been inserted into a tube Furnace as shown in Fig. 1 and the temperature was increased from 35°C to 1075 °C. The dynamics of the grating reflectivity during this thermal treatment is shown in Fig. 4. As the temperature increases the normalized reflectivity is found to be constant up to 650<sup>0</sup> C. Later there is an exponential decrease in the reflectivity. Again, the reflectivity was found constant within 1000<sup>0</sup> C to 1100<sup>0</sup> C. A second peak in the reflected spectrum was noticed at 760<sup>0</sup> C as shown in Fig. 5 (a). This is probably due to increase in concentration of OH ions which form Ge-OH and Si-OH molecules in the fiber. The absorption of spectral wavelength is different for these two molecular species [13]. The reflectivity of the second peak gradually increased with temperature. At temperature 955<sup>0</sup>C, reflectivity of both the peaks is the same. Further increase in temperature shows the increase in wavelength separation between the two peaks as shown in Fig. 5 (b). Further increase in temperature resulted in the decay of the type-I grating, which is consequently erased at 170 minutes. The grating was stable and continued to survive throughout the rest of the experiment up to 1075°C [14-15].



(a)



(b)

Fig. 5. Appearance of second peak at: (a) 760°C temperature; (b) 1000°C temperature.

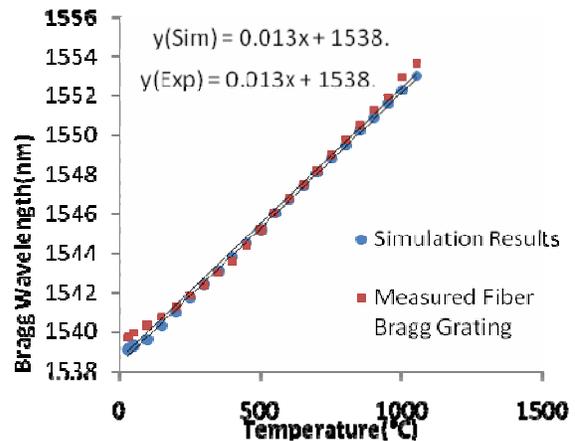


Fig. 6. Spectral shift of the reflection peaks as a function of increasing the temperature from 35°C to 1075°C.

The temperature dependence of the resonance wavelength of an FBG was also experimentally studied. The temperature is measured on the basis of the shift in wavelength of the FBG reflection peak. Increasing the temperature from 35°C to 1075°C the shift of Bragg wavelength from 1539.662 to 1553.55nm was observed as shown in Fig. 6. The temperature sensitivity of the grating was found to be 13.68 pm/°C with linearity of 99.4%. Theoretical analysis was carried out using MATLAB

software. The sensitivity of the experimental and theoretical results very closely matched.

Observation of the temperature response of the same FBG from 1100°C to 35°C reveals that as the temperature decreases the two peaks and their wavelength separation decrease at 1000°C as shown in Fig. 7 (a). Further with the decrease of temperature the two peaks merge together and form a single peak with increased intensity at around 800°C [16] as shown in Fig. 7 (b).

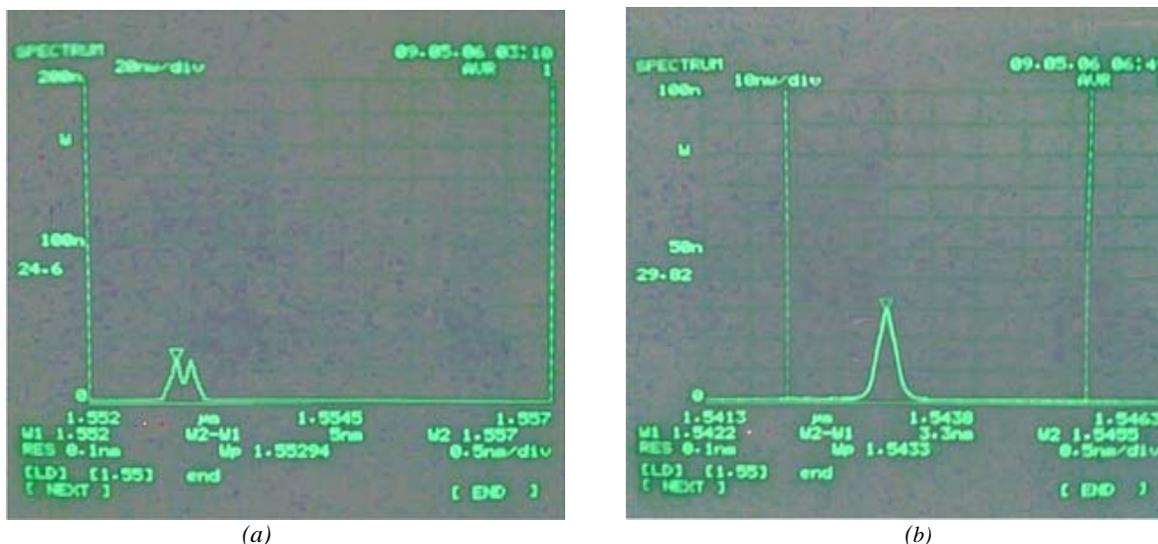


Fig. 7. Evaluation of regenerated grating at (a) 1000°C temperature (b) 400°C temperature.

Table 1. Parameters of the FBGs measured.

| Parameter   | Without hydrogen loaded fiber | With hydrogen loaded fiber |
|---|-------------------------------|----------------------------|
| Bragg wavelength $\lambda_B$ (nm) at room temperature | 1535.8                        | 1539.66                    |
| Grating length (mm)                                   | 3                             | 5                          |
| Initial reflectivity at room temperature R(%)         | 90                            | 95                         |
| completely erased at temperature                      | 825°C                         | 1100°C                     |

### 3. Results and discussion

The non hydrogenated fiber is found to be thermally stable at lower temperatures. With increasing temperature, the reflected peak power is exponentially decreasing and it shows anomalous behavior. Further, regenerative property is not noticed. In hydrogen loaded fiber, experimental results show the survival of grating approaching to 1075°C. Although the grating strength diminished significantly, there was complete recovery when cooled back to room temperature. The decrease in grating strength can be attributed to the changes in core cladding index contrast as the core has larger expansions coefficient than the cladding.

It is also observed that at any given temperature, the same wavelength shift is noticed while the temperature is increasing or decreasing as shown in Fig. 8. The rates of shift of wavelength values are exactly coinciding while the temperature is increasing or decreasing as shown in Fig. 9. This proves the existence of regenerative property of hydrogen loaded fiber grating [17]. Because of this regenerative property, there is no anomalous effect of temperature over wavelength and no change was noticed in the structure or anomalous property of the FBG. These results indicate that this grating performs reliably as ultra high temperature component and sensor applications.

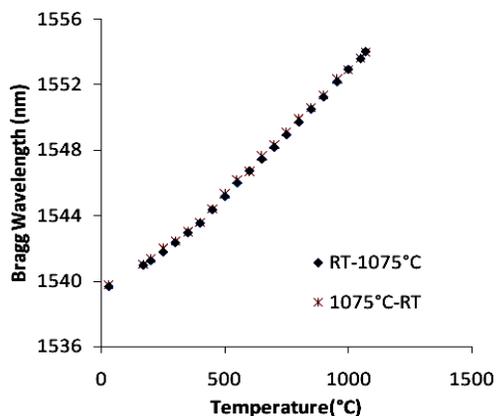


Fig. 8. Measured Bragg wavelength during high temperature cycle (room temperature [RT] to 1075 °C and back).

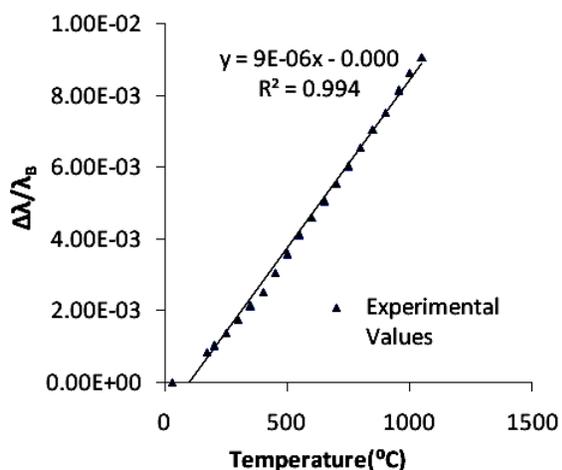


Fig. 9. Rate of shift of wavelength vs temperature during temperature cycle (room temperature to 1075°C).

#### 4. Conclusions

The thermal erasure dynamics of the FBGs written in hydrogen loaded and non-hydrogen loaded fibers have been studied in the temperature range of 35°C to 1075°C. The temperature response of the gratings during the above temperature range has been experimentally found and compared with theoretical simulations using MATLAB. It was found that the FBGs written in hydrogen loaded fibers are thermally stable compared to the ones written in non hydrogen loaded fibers. Also, the response of the hydrogen loaded fibers is found to be linear and non anomalous.

#### Acknowledgements

The authors thank Prof. John Canning, University of Sydney, Australia for providing hydrogen loaded FBGs and Prof. S. Asokan, Indian Institute of Science, Bangalore, India for providing the experimental facilities for conducting this experiment.

#### References

- [1] D. P. Hand, P. St. J. Russell, *Opt. Lett.* **15**(2), 102 (1990).
- [2] T. Erdogan, V. Mizrahi, P. J. Lemaire, D. Monroe, *J. Appl. Phys.* **76**(1), 73 (1994).
- [3] J. L. Archambault, L. Reekie, P. St. J. Russell, *Electron. Lett.* **29**(5), 453 (1993).
- [4] N. Groothoff, J. Canning, *Opt. Lett.* **29**(20), 2360 (2004).
- [5] D. L. Williams, B. J. Ainslie, J. R. Armitage, R. Kasyap, R. Campbell, *Electron. Lett.* **29**, 45 (1993)
- [6] E. M. Dianov, K. M. Golant, V. M. Mashinsky, O. I. Medvedkov, I. V. Nikolin, O. D. Sazhin, S. A. Vasiliev, *Electron. Lett.* **33**, 1334 (1997)
- [7] T. A. Strasser, A. E. White, M. F. Yan, P. J. Lemaire, T. Erdogan, in *Proc. Optical fiber Conference OFC'95*, Paper WN3, 1995.
- [8] M. Fokine, *J. Opt. Soc. Am. B* **19**(8), 1759 (2002)
- [9] M. Fokine, *Optic Letters.* **29**(11), 1185 (2004)
- [10] A. Rahman, K. VenuMadav, B. Srinivasan, S. Asokan, *Optoelectron. Adv. Mater.-Rapid Comm.* **3**(1), 17 (2009)
- [11] Y. Shen, J. He, Y. Qiu, *J. Opt. Soc. Am. B* **24**(3), (2007).
- [12] J. Canning, M. Stevenson, S. Bandyopadhyay, K. Cook, *Sensors* **8**, 6448 (2008).
- [13] H. R Sorensen, J. Canning, M. Kristensen, *Optics Express.* **13**(7), 2276 (2005).
- [14] J. E Shelby, *J. Appl. Phys.* **51**(5), 2589 (1980).
- [15] A. H. Rose, *The American ceramic society Bulletin.* **79**(3), 40 (2009).
- [16] E. Lindner, C. Chojetzki, S. Bruckner, M. Becker, M. Rothhardt, H. Bartelt, *Optics Express.* **17**(15), 12523 (2009).
- [17] G. Simpson, K. Kalli, K. Zhou, L. Zhang, I. Bennion, *Meas. Sci. Technol.* **159**, 1665 (2004).

\*Corresponding author: physicsnitw@gmail.com