Fiber Bragg Grating Regeneration Modeling and Ultra-wide Temperature Sensing Application

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ABSTRACT

Three types of Fiber Bragg gratings (FBGs) were inscribed in H_2-loaded and H_2-free fiber with phase mask using 800nm femtosecond (fs) laser, ultraviolet (UV) excimer laser respectively. Their reflection spectra regenerating procedure were observed under different annealing temperature and the models of regeneration process as well as annealing temperature and time were established. Experiments and model fitting show that there were definite regeneration temperature threshold for fs FBGs written in H_2-free fiber, H_2-loaded fiber and UV FBGs in H_2-loaded fiber. The temperature sensing characteristic of RFBGs were investigated and compared experimentally under ultra-wide temperature range.

Keywords: femtosecond laser, regenerated fiber Bragg grating, threshold, temperature sensing,

1. INTRODUCTION

Fiber Bragg gratings (FBGs) attracted a large number of researchers attention due to its immunity to EM interference, inherent spectral characteristics, which allowed the development as plenty of sensing applications[1,2]. Regenerated fiber Bragg gratings (RFBGs),which can be used in sensing network under ultra-high temperature, were first produced by Michael Fokine in 2002 and this phenomenon was interpreted with the concept "chemical composition gratings (CCG)" [3]. In 2008, John canning manufactured RFBGs seeded by type I grating in boron-codoped germanosilicate optical fiber written with 193nm laser, which is shown withstand temperature cycling up to 1295℃[4]. Soon afterwards, John canning's team obtained ultra-strong RFBGs in strength by increasing the length of gratings and using a small core high NA germanosilicate fiber[5]. Eric Lindner reported a thermal RFBGs written in photosensitive fibers without hydrogen loading by nanosecond laser pulse in 2009[6]. Such type of gratings is well suitable for sensing in a temperature range up to at least 550℃ and with good spectral reflection characteristics. In 2012, K. cook demonstrated RFBG inscribed by direct writing using a femtosecond, infrared laser into SMF-28 and pure silica core fibers[7]. This kind of RFBGs could survive in temperature up to 1200℃. The first time RFBG operating at an ultra-high temperature up to 1400℃ was proposed by Hangzhou Yang in 2014[8]. A new class of photosensitive optical fiber based on erbium-doped yttrium stabilized zirconia-calcium-alumina-phosphor silica was used to make this RFBGs. However, the regeneration anneal temperature and period vary in different researches, from 600 to 1000 ℃, minutes to hours or so[9]. Threshold notion of RFBGs processed temperature was proposed but there was no exactly model.

In this paper, we demonstrated RFBGs seeded in FBGs inscribed in H_2-loaded and H_2-free fiber with phase mask using 800nm femtosecond (fs) laser, UV excimer laser respectively. Their reflection spectrum regenerating procedure were observed under different annealing temperatures and the models of regeneration process as well as annealing temperature and time were established. Temperature sensing experiment was conducted with the range from -196 to 1200℃ with liquid nitrogen canister and high temperature tube furnace.

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2. FBGS REGENERATING AND MODELING

2.1 Seed FBGs Fabricated

The experimental setup used for FBGs gratings fabricating was shown in Fig.1. This is a typical FBGs inscribed setup, composed of laser (800nm fs laser or UV laser pulses), waveplate, polarizer, cylindrical lens and phase mask. The beam was focused by a cylindrical lens through a phase mask onto the fiber core. Bragg gratings are inscribed in Corning SMF-28 which was loaded with hydrogen (10 MPa, 80 °C for 7 days). Three types of FBGs were inscribed in H_2-loaded and H_2-free fiber with phase mask using 800nm femtosecond (fs) laser (abbreviated to fs H_2-loaded FBGs and fs H_2-free FBGs respectively), UV excimer laser (abbreviated to UV FBGs) respectively. The typical transmission and reflection spectra of FBGs were shown in Fig.2.

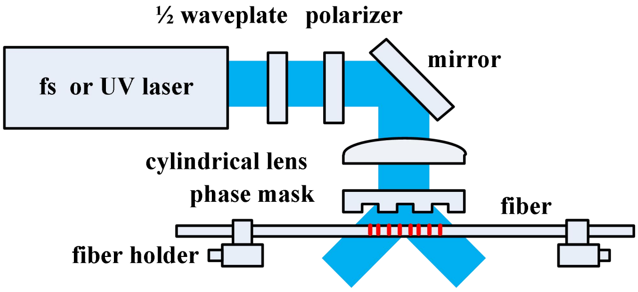

Fig.1. Schematic diagram of seed FBGs fabricated system

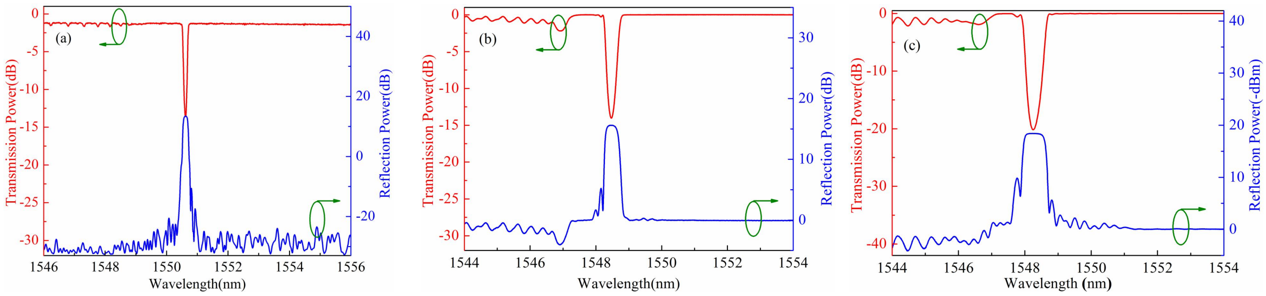

Fig.2. Typical transmission and reflection spectra of FBGs. (a) UV-FBGs; (b) fs H_2-load FBGs; (c) fs H_2-free FBGs

2.2 FBGs regenerating experiments

The FBGs regenerating experiment system was illustrated in Fig.3, which was composed FBGs interrogator (SM125), a high temperature furnace (FNS SK-3-12Y) with a thermocouple. As shown in Fig.3, the seed FBGs were placed loosely in the resistance-heated tube furnace which operating temperature can be up to 1200 ℃. The total length of the furnace is 500 mm with 200 mm isothermality region. The thermocouple is placed at the middle of this region to monitor the temperature in furnace tube and the temperature in furnace was recorded by thermometer. The spectra and the central wavelengths were recorded by SM125 interrogator.

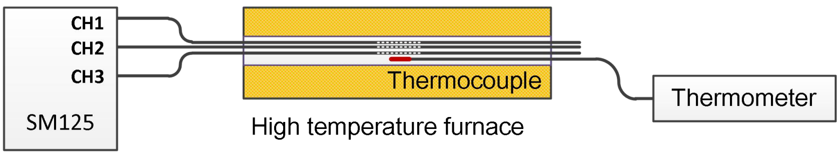

Fig.3. Illustration of FBGs regenerating setup

Three types seed FBGs were annealing under700℃, 800℃, 900℃, 1000℃, 1100℃, respectively. The temperature ramped with step of 100℃ and kept at the set annealing temperature. The wavelength and peak power of reflection spectrum of FBGs during annealing under 800℃ temperature were shown in Fig.4 as a typical RFBGs procedure curves. The regeneration time was defined as *t*, which was the difference value between the time when the temperature reached set temperature and the time when the peak power of RFBGs reflection spectrum reached steady state (90% of maximum of peak power). The annealing temperature and corresponding regeneration times were listed in Table 1. Regeneration phenomenon did not occurred for all three types seed FBGs under 700℃ annealing temperature and for fs H_2-free FBGs only under 800℃ annealing temperature. This suggested that regeneration phenomenon was dependent on annealing temperature and there may be regeneration temperature threshold.

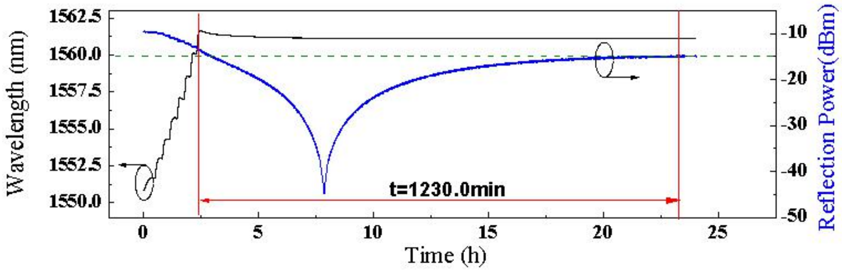

Fig.4. Typical regeneration FBGs procedure curves

Table 1.The regeneration experimental results

Type of FBGs	Annealing temperature (℃)	Regeneration time (min)
fs H_2-load FBGs	700	--
	800	1230.0
	900	91.2
	1000	11.2
	1100	2.3
fs H_2-free FBGs	700	--
	800	--
	900	606.0
	1000	59.3
	1100	23.7
UV FBGs	700	--
	800	1256.3
	900	137.6
	1000	12.7
	1100	3.5

2.3 Regeneration Temperature Modeling

To describe the regeneration procedure of RFBGs, the hyperbolic function of *csch* was taken and the regeneration temperature modeling equation can be written as following:

$$t = A \cdot \mathrm{csch}\left(\frac{T - T_{\mathrm{th}}}{B}\right) \tag{1}$$

Where: *t* was regeneration time, *T* was annealing temperature, T_{th} was regeneration temperature threshold. *A* and *B* were model parameters for certain type of FBGs. The regeneration temperature threshold and parameters of three types of

FBGs were obtained by nonlinear curve fitting method with data in Table 1 and was listed in Table 2. The curve of regeneration time vs. annealing temperature was plotted in Fig.5. The experimental and model fitting results show that there were definite regeneration temperature threshold for certain FBGs and the regeneration threshold temperatures were around 888 ℃, 780 ℃ and 770 ℃ for fs H_2-load FBGs, fs H_2-free FBGs, UV FBGs respectively. It may suggest that hydrogen hyper-sensitization helps eliminate the divergence of UV laser and infrared laser inscription technique.

Table 2.The model parameters of regeneration temperature model of RFBGs

Type of FBGs	*A*	*B*	T_{th} (℃)
fs H_2-load FBG	516.20536	48.58572	780.2
fs H_2-free FBG	47.43426	146.4923	888.5
UV FBG	705.83248	54.77441	770.7

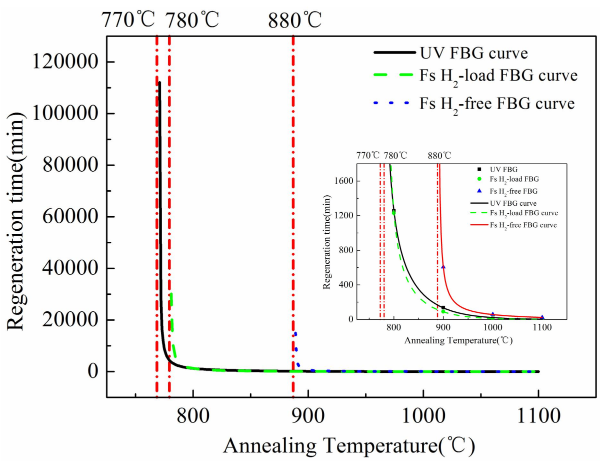

Fig. 5 The curve of regeneration time vs. annealing temperature

3. THE TEMPERATURE SENSING CHARACTERISTIC OF RFBGS

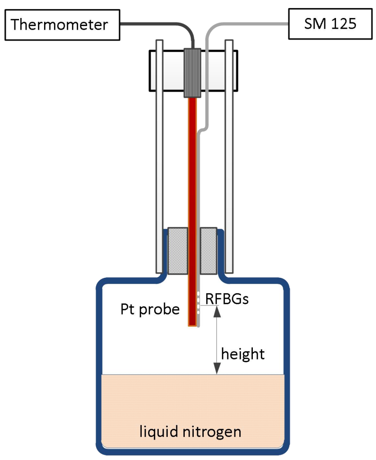

Fig.6 Low temperature measure setup

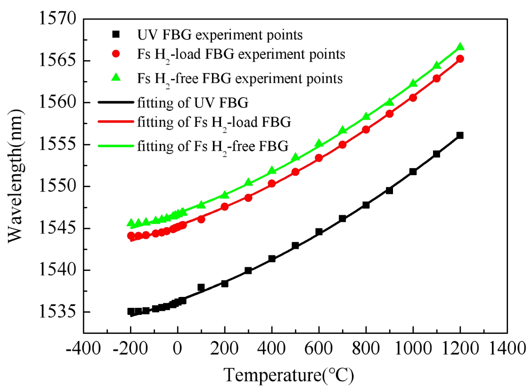

Fig.7 Wavelength response of RFBGs within -196~1200℃

The temperature sensing characteristic of RFBGs regenerated from UV FBG, fs H_2-load FBG and fs H_2-free FBG were tested within temperature range from -196 to 1200℃. The high temperature range (room temperature to 1200℃) testing was carried out with setup shown in Fig. 3.The setup for low temperature range （-196 to room temperature） testing was shown in Fig.6. The liquid nitrogen canister was used to form low temperature condition. A standard platinum resistance thermometer was used to monitor temperature and taken as reference temperature. RFBGs under test were mounted with this thermometer probe, as shown in Fig.6. So temperature applied on RFBGs can be measured by contrast test method. Changing the height between RFBGs and surface of liquid nitrogen, various test temperature could be obtained. During testing, temperature interval was set as about 10℃ which corresponding to about 2cm height and the reflection spectrum of RFBGs was recorded with SM125 interrogator. The two temperature ranges test was carried out independently. The wavelength response vs. temperature of RFBGs were combined and plotted in Fig.7. All of three types of RFBGs have lower sensitivity in low temperature range. Quadratic polynomial could be used to fit the wavelength response vs. temperature within Ultra-wide temperature range and the average sensitivity of three types of RFBGs are 10.05pm/℃, 10.08pm/℃, 10.13pm/℃ respectively.

4. CONCLUSION

The regeneration characters of FBGs inscribed in both H_2-loaded and H_2-free SMF using UV laser and 800nm femtosecond laser were investigated and the regeneration temperature model was obtained with the experimental data. This model may help to full understanding of the mechanism of seed grating and RFBG formation. The model of FBGs regeneration provides a practical procedure of RFBGs fabrication. The RFBG has high potential for ultra-wide temperature sensing.

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