HIGH TEMPERATURE FBG SENSOR

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ABSTRACT
A novel high temperature resistance FBG temperature sensor, which base on the hydrogen loaded germanium doped FBG, is developed. The tested gratings have shown stabilized at temperatures in excess of 1000°C. Due to the high bonds energy of hydroxyl and the low diffusivity of the molecular water, the thermal testing results of this FBG temperature sensors show the thermal stability of hydrogen loaded FBG can be increased using annealing treatment; moreover, the highest erasing temperature for this type temperature sensor is more than 1000°C.

Keywords: Sensors, Fiber Optics, High Temperature, FBG

1. INTRODUCTION

The principle of the dielectric Bragg grating temperature sensor is based on the measurement of the reflected Bragg wavelength. Recently, the most popular design is the Fiber Bragg grating (FBG). Fiber gratings are compact intrinsic sensing elements, which are relatively inexpensive to produce, easy to multiplex, and applicable to a range of physical measurands [1]. A FBG is formed by a periodic change in the refractive index caused of a fiber core by exposure to an UV laser beam [2].

One of the advantages of FBG temperature sensors is that several of these sensors can be multiplexed in series along with a single optical fiber so that a single instrument can simultaneously monitor many individual sensors [3]. Additionally, the FBG temperature sensor also has some other advantages such as resistant to electromagnetic interference, tiny volume and light weight; however, it has also some serious disadvantages. The FBG exhibit poor stability within the high temperature environment and the grating can be completely erased at temperature around 700°C [4]. Because of above mentioned reasons, nowadays, the grating based temperature sensors are usually used under 200°C due to decay of the FBGs reflectivity, especially the decay of the hydrogen loaded FBGs [5]reflectivity.

2. MOLECULAR WATER INDUCED FBG

High pressure hydrogenation of germanium doped fibers can significantly enhance photosensitivity within optical fibers and produce strong FBGs with 248 nm or 193 nm laser [6]. One of the expert explanations for this phenomenon can be deduced from the concentration of germanium–oxygen-deficient center (GODC) [7, 8] and drawing induced defect (DID trapped hole with an oxygen vacancy) [8, 9] inside optical fiber. Due to the hydrogenation of the conventional (SMF-28) optical fiber, a big amount of GODC (compare with non-loaded fiber) will be engenders by irradiating a pulse UV radiation in the hydrogen loaded area. An excited GODC, which is a GODC absorb a photon at wavelength at 240 nm, can ionize spontaneously or
by absorbing another 240 nm photo-such ionization is thought to be necessary for an index change. However, the mostly excited GODC will relax to the long-lived triplet-stat and changes the GODC structure to a DID. The structural rearrangement of GODC into the DID is the principal cause of light induced refractive index modulation inside germanium doped and hydrogen loaded optical fiber.

\[ \text{Si}-\text{O} \rightarrow \text{Ge} \rightarrow \text{Si} \equiv + \text{H} + \text{H} \rightarrow \text{Ge}^* + 2\text{(H-O-Si =)} \]  

(1)

\[ \text{Ge} \rightarrow \text{Si} + \text{O} \equiv + \text{H} + \text{H} \rightarrow \text{Si}^* + 2\text{(H-O-Ge =)} \]  

(2)

\[ \text{Ge}^* + \text{O} \equiv \rightarrow \equiv \text{Ge}^* + \text{Si} \equiv \]  

(3)

\[ \text{Si}^* + \text{O} \rightarrow \equiv \rightarrow \equiv \text{Ge}^* + \text{Si} \equiv \]  

(4)

where \( h\nu \) is the energy of the absorbed UV photon. The absorption presents at 240 nm (5.1 eV) mainly.

Ge-O bonds play the important role during the index change process. This bonds are broken by UV laser and then react with hydrogen to produce hydroxy and the DID. If the fiber Bragg grating is annealed at high temperature, it will react with the DID. The Ge-O bonds are weaker than Si-O bonds (Ge-o-Ge is 4.2 eV, Ge-O-Si is 4.5 eV, and Si-O is 5 eV) [10] and the Ge-O bonds can be more readily broken by low energy radiation. One of the weakest bond from the three bonds of the DID (trapped hole with an oxygen vacancy) will be broken by annealing treatment. Therefore the thermal induced structural change from DID into the GODC is the principal cause of thermal decay of fiber Bragg grating refractivity.

3. EXPERIMENTAL RESULTS

In this work, three hydrogen loaded FBGs, Sample A, B, and C, were tested for the absorption spectra between 1.34 µm to 1.44 µm in our laboratory. The different parameters of the Fiber Bragg gratings fabricated in different fibers are described in Table 1. The measured absorption spectra illustrate in Figure 3. The spectrum profile of absorption in UV exposed fibers consists of two distinct peaks associated with Ge–OH and Si–OH formation. In Fig. 3, Si-OH and Ge–OH absorption bands for the first vibration overtone are 1.39 and 1.41 µm respectively.

![Absorption spectra of hydrogen loaded FBG near 1.4 µm](image)

The interaction of hydrogen molecules at Ge or Si tetrahedral sites inside the fiber core leads to enhanced permanent UV induced losses, particularly due to the increase in the OH content in the fiber. In general, the hydrogen molecules react at normal Si-O-Ge sites, resulting in the
formation of Si-OH and oxygen deficient Ge defects, both of which contribute to the observed index change. Reflectivity of hydrogen loaded germanium doped FBG depends on refractive index modulation in the fiber core and indirect related to the amount of the Ge-OH and Si-OH in the UV exposed rear of optical fiber core. Obviously, in Fig. 3, the concentration of Ge-OH was directly related to doping concentration of Ge inside the optical fiber core and the distinctness of the refractive index modulation for testing samples was based on the amount of Si-OH.

Molecular water is another type of impurity inside optical fiber core. The near infrared absorption of molecular water had peak absorption at 1.42 µm. However, the spectrum profile of absorption for water was commonly covered up by the spectrum profile of Ge-OH absorption.

After exposing the loaded fiber to UV laser, the FBG samples were diffused hydrogen out of the fiber by heating for 40 seconds at 350 °C, and then were performed by a series of annealing testing in an electronic furnace. For the OH absorption experiment of FBG, FBG’s sample C was annealed inside the furnace from room temperature (22.5 °C) up to 500 °C. At each new temperature point, the tested FBG was treated with isothermal annealing for 10 minutes and then its OH absorption spectrum and its reflectivity were measured.

Fig. 4. Normalized magnitude changes of Si-OH absorption (1.39 µm), Ge-OH absorption (1.41 µm), and water absorption (1.42 µm) versus annealing temperature.

Fig. 5. Normalized magnitude changes of FBG index modulation versus annealing temperature.

Fig. 4 is synoptically described the relationship between the components of Ge-OH, Si-OH,
and molecular water inside optical fiber core. In a higher temperature range, thermal decay of the hydrogen loaded FBG can be described as the process of Si-OH decomposition and relate to the amount of Si-OH as well as the defect of Si-OH. The highest decomposition temperature for the hydrogen loaded FBG is around 940 °C, which is indicated in Fig.6.

Molecular water is the essential part of the high temperature resistance FBG. In theory, the molecular water formation inside FBG roots in the decomposition of the Si-OH and the composition from OH group synchronously. In our experiments, the molecular water induced reflectivity was observed starting at temperature around 950 °C. The molecular water induced reflectivity of FBG, which shows in Fig.7, can be described as two correlative steps: the grating grown up (950 °C to 1000 °C in Fig. 7) and the grating stabilization (isothermal annealing at 1005 °C).

4. PERFORMANCE OF FBG DURING THERMAL EVALUATION

To test the characteristics of molecular water induced FBG in thermal annealing, the transmitted spectra of the tested specimen was measured from room temperature to 1000 °C. Fig. 8 reveals the reflectivity of tested FBG in the different annealing temperature ranges. The
molecular water induced FBG has extremely stable reflectivity at the high temperatures compare with the conventional FBGs.

![Fig. 8. Reflectivity versus temperature for molecular water induced FBG from room temperature to 1000 °C.](image)

The shift of the Bragg wavelength with temperature has been widely used as an effective factor for temperature sensing or temperature compensation in other sensors. The temperature sensitivities of the gratings were determined by observing the change of Bragg wavelength with temperature. The spectral response of molecular water induced FBG was displayed in Fig. 9. This results show the sensitivity of the molecular water FBG is slightly higher than the conventional hydrogen loaded FBG (0.0166 nm/°C compare with 0.015 nm/°C [11]at temperature around 700°C). As the figure shows, this variation of the sensitivity with respect to temperature is not linear but fits a second order polynomial.

![Fig. 9. Bragg wavelength versus temperature for molecular water induced FBG from room temperature to 1000 °C.](image)

5. CONCLUSION

The high temperature FBG sensor based on the hydrogen-loaded FBG has been designed,
developed, and tested. Thanks to this new development, a FBG thermometer with a temperature ranging from room temperature to over 1000°C was realistically performed.

In this high temperature resistance FBG, its refractive index is formed by a periodic modulation of molecular water inside the fiber core. The molecular water induce FBGs were produced through a hydrogen loaded conventional fiber with 248 nm UV laser as well as thermal processing technique. The recorded spectra shows the tested FBG are exceptionally stable at high temperatures; besides, the spectral response of tested FBG does not differ from hydrogen loaded FBGs.

As a result of the thermal stability, molecular water induced FBGs are ideally temperature probes for sensor applications in high temperature environments. Any slight change in temperature can be detected directly by monitoring the change in the reflected wavelength of the grating with 0.5 °C temperature resolutions at 1000 °C.

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7. REFERENCES
